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FINAL REPORT ON THE  
1989 LIME TREATMENT  
OF HALFMOON LAKE

CANADIANA

MAR 26 1991





## Executive Summary

In late July 1988, Halfmoon Lake, located in the County of Strathcona was treated with two forms of lime (58 Tonnes of  $\text{CaCO}_3$  and 49 Tonnes of  $\text{Ca(OH)}_2$ ). This treatment was intended to suppress both algal biomass and total phosphorus concentrations.

## FINAL REPORT ON THE 1989 LIME TREATMENT OF HALFMOON LAKE

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## Executive Summary

In late July 1988, Halfmoon Lake, located in the County of Strathcona was treated with two forms of lime (58 Tonne of  $\text{CaCO}_3$  and 49 Tonne of  $\text{Ca(OH)}_2$ ). This treatment was intended to suppress both algal biomass (as estimated by chlorophyll a concentration) and total phosphorus concentration (the major algal nutrient). In the fall and winter of 1988-89, total phosphorus concentrations in the open water were lower than in the previous year on record. Further, in the spring of 1989 chlorophyll a and phosphorus concentrations were only 30 and 50%, respectively, of historic levels (i.e. 1982).

During the open-water period in 1989, both total phosphorus and chlorophyll a concentrations were lower than for the previous five years on record. However, an algal bloom developed in mid-July 1989, even though total phosphorus concentrations were significantly reduced compared to previous years. This algal bloom was small, relative to historical algal blooms recorded in Halfmoon Lake. In early August 1989, an additional 139 Tonne of  $\text{Ca(OH)}_2$  was added to the lake to enhance the suppression of total phosphorus and chlorophyll a concentrations in the open water.

We are evaluating changes in water and sediment chemistry which accompanied the 1988 and 1989 lime treatments of Halfmoon Lake. This winter, dissolved oxygen concentrations in Halfmoon Lake are significantly higher than historic values for this lake. Furthermore, total phosphorus concentrations are reduced relative to previous years on record. It is anticipated that the lower total



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phosphorus concentrations under ice-cover will result in low chlorophyll a concentrations during the summer of 1990.

Halfmoon Lake presents an excellent opportunity to evaluate the ability of lime to control total phosphorus and chlorophyll a concentrations in lakes: it has a relatively good historic data base, troublesome algal blooms, and two years of well documented lime treatments. A cooperative research program between the Alberta Environmental Center and the University of Alberta has been formulated and is included as an appendix to this report; Halfmoon Lake is included in this program. The proposed program focuses on changes to the sediment phosphorus binding capacity as an index of sediment phosphorus mobility and thus lake water quality.

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## GLOSSARY

This glossary contains limnological terms used in this report. Contractions of these terms are given in round brackets (). Square brackets[] around the contraction indicate 'concentration'. eg. Dissolved oxygen: (DO):[DO].

**Algae** - small, usually microscopic plants.

**Algal bloom** - Floating mat of algae (usually blue-green); commonly found on the surface of eutrophic lakes on hot summer days.

**Biomass** - The weight of living material (in a given unit volume).

**Chlorophyll a** - (Chla); A green pigment important for photosynthesis. When measured in the water column, it can provide an estimate of phytoplankton (algal) biomass.

**Dissolved Oxygen** - (DO); oxygen dissolved in the water.

**Epilimnion** - The warm, circulating and fairly turbulent surface water layer of a thermally stratified lake.

**Eutrophic** - Describes water bodies rich in nutrients which are therefore highly productive. Typically, eutrophic lakes experience severe algal blooms in the summer and dissolved oxygen depletion and fish kills in the winter.

**Hypolimnion** - The cold, dense and relatively undisturbed deep water layer of a thermally stratified lake.

**Internal Loading** - The release of nutrients into the water column from the bottom sediments in a lake. This process is prevalent under conditions of low [DO].

**Secchi Disk Depth** - The depth to which a black and white circular disk remains visible from the surface of the water column.

**Thermal Stratification** - Occurs when a lake has two distinct layers: a warmer, less dense upper layer (epilimnion) and a colder, denser lower layer (hypolimnion). These two layers do not mix.

**Total Phosphorus** - (TP); the nutrient which is usually limiting for algal growth in a lake.

**Total Dissolved Phosphorus** - (TDP); The phosphorus in lake water which passes through a 0.45-um membrane filter. Much of this phosphorus may be available for plant growth.

**Winter Oxygen Depletion Rate** - (WODR); the rate at which DO is depleted in the water during the winter.





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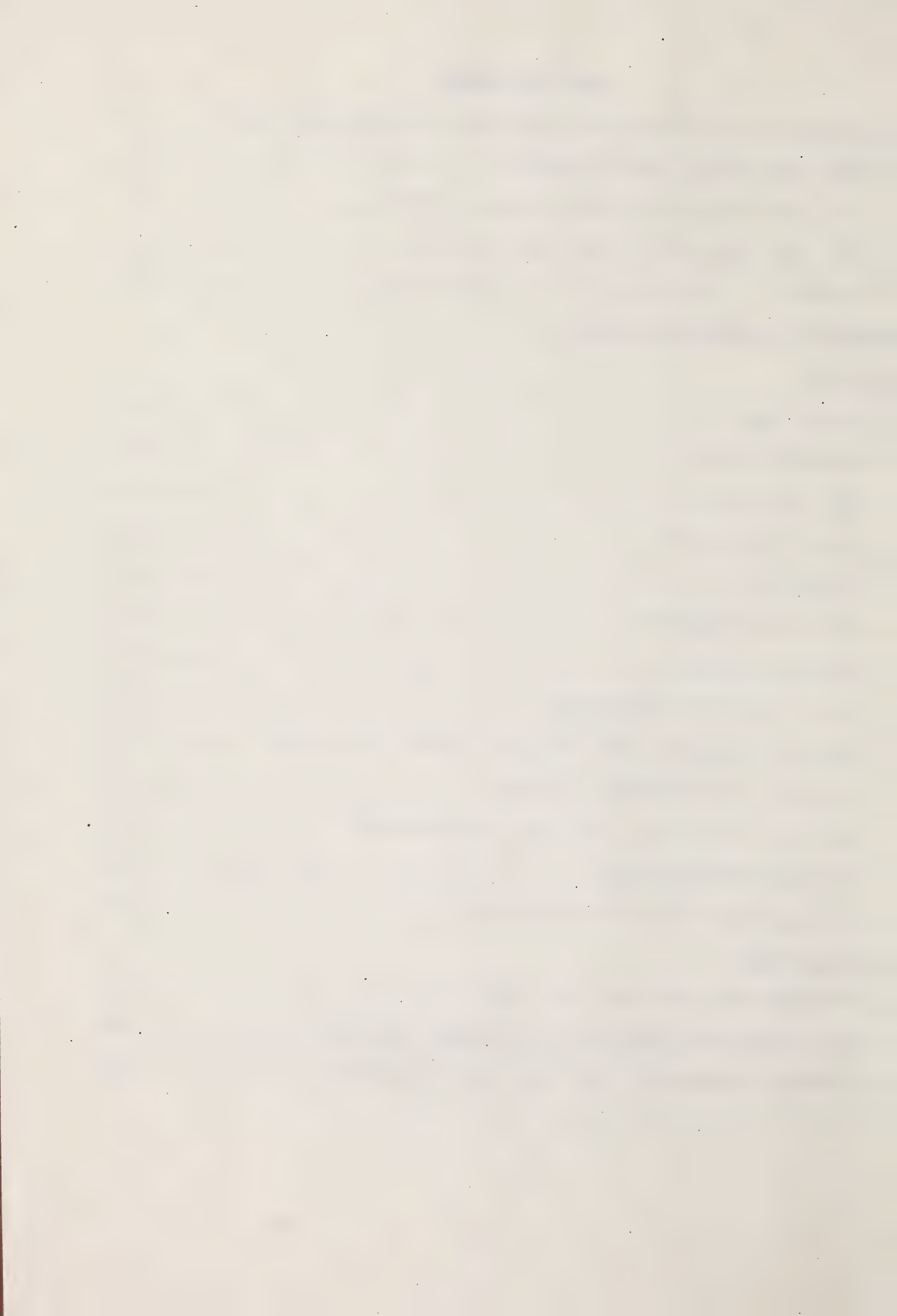
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## 1. INTRODUCTION

### 1.1 Study Area

Halfmoon is a small (surface area of  $0.41 \text{ km}^2$ ) lake located approximately 20 km southeast of Edmonton. It is situated in the Cooking Lake moraine. Soils in the area are Orthic Gray Luvisols; dominant trees are trembling aspen and balsam poplar. Baseline information on Halfmoon Lake and its drainage basin are summarized in Table 1.

Table 1. Characteristics of Halfmoon Lake and its drainage basin<sup>1</sup>

#### Halfmoon Lake

|                         |                    |
|-------------------------|--------------------|
| area ( $\text{km}^2$ )  | 0.41               |
| volume ( $\text{m}^3$ ) | $1.96 \times 10^6$ |
| max depth (m)           | 8.5                |
| mean depth (m)          | 4.7                |

#### Drainage Basin

|                                |                     |
|--------------------------------|---------------------|
| area ( $\text{km}^2$ )         | 2.43                |
| annual inflow ( $\text{m}^3$ ) | $0.114 \times 10^6$ |
| residential lots               | 35 houses           |
| commercial sites               | 1 campground        |

---

<sup>1</sup>Adapted from the Atlas of Alberta Lakes (1990)

### 1.2 Historical Water Quality

From 1955 to the present, water samples have periodically been obtained from Halfmoon Lake to determine water quality characteristics by: Fish and Wildlife Division, Alberta Environment, and the University of Alberta. Halfmoon Lake is classified as hyper-eutrophic; characteristics of hyper-eutrophic lakes of similar depth are:

- high nutrient concentrations
- high algal biomass and massive blooms of blue-green algae
- extensive macrophyte beds

- low water clarity
- summer- and winterkill of fish (if a fish population is present)
- almost total or total anoxia for part of the winter
- highly organic sediments

All of these features have been documented for Halfmoon Lake.

Despite repeated attempts at fish stocking and winter aeration (Bidgood 1967), no sport fishery has developed in Halfmoon Lake.

### 1.3 Basis for Lime Treatment

In 1988, an experimental project to reduce [TP] and [Chl<sub>a</sub>] in Halfmoon Lake was initiated by the County of Strathcona, Halfmoon Lake Resort, Alberta Environment, and the University of Alberta. In July 1988, 58.1 Tonne of CaCO<sub>3</sub> and 48.7 Tonne of Ca(OH)<sub>2</sub> were added to the lake. During 1989, mean and maximum [TP] and [Chl<sub>a</sub>] were lower than any previous year on record. Even though [TP] and [Chl<sub>a</sub>] were significantly reduced in the lake compared to previous years, concern about a July algal bloom developed and an additional 138.6 Tonne of Ca(OH)<sub>2</sub> was added to Halfmoon Lake from 8 to 17 August 1989.

The final details of a joint research program on the use of lime for lake restoration are presently being worked out between the University of Alberta and the Alberta Environment Center at Vegreville. It is anticipated that this program will continue for four to five years, and will include Halfmoon Lake. The details of this research proposal are in Appendix A.



## 2. METHODS

### 2.1 Sample Collection

In 1989 Halfmoon Lake was sampled weekly from 9 May to 28 August, and twice in both September and October. On each sampling trip, water samples were collected with a 1.5-L aluminum drop-sleeve water sampler at the deepest site. These samples were used to construct vertical profiles of specific water quality parameters. Water samples were collected every meter for analyses of [DO], and at 0-, 1-, 2-, 4-, 6-, and 7.5-m depths for analyses of [TP], [TDP], conductivity, pH, alkalinity, color, turbidity, major cations (Ca, Mg, Na, and K), [NO<sub>2</sub> + NO<sub>3</sub>], and [NH<sub>4</sub><sup>+</sup>]. Temperature and light levels were also measured at 1-m depth intervals throughout the water column at the deep site, and Secchi disk depth was determined.

An integrated (0- to 2.5-m) composite (from 8 sites) water sample was also collected every sampling trip for analyses of the above parameters as well as [Chl<sub>a</sub>] and phytoplankton species composition and biomass.

pH was measured *in situ* at two sites during application of lime with a portable pH meter; at the private beach on the southeast shore of the lake and at the site where lime was loaded onto the barge. All other pH measurements were performed in the laboratory at the University of Alberta.

Three sets of porewater samples were collected at one site in the lake where the water depth was 2.0 m. Porewater samples were collected with *in situ* samplers called peepers (Hesslein 1976). The samplers were placed in the lake on 5 September 1989, and were

removed on 26 October 1989. Water samples collected from the peepers were analyzed for [DO], soluble reactive phosphorus, and  $\text{Fe}^{2+}$  concentrations.

Sediment cores were collected twice during the summer of 1989: 1 August (pre-1989 treatment) and 19 September (post-1989 treatment). The sediment cores were collected with a K-B corer from three sites in the lake, at water depths of 5.1, 5.6 and 8.0 m. The uppermost 10 cm of the core were sliced at 1-cm intervals and, thereafter every 5 cm. Sediment slices were frozen for later analyses of organic content, major ions, and phosphorus content. These cores will be compared with sediment cores collected in 1988 (pre-treatment) from Halfmoon Lake.

Three sediment traps (each trap with three barrels) with aspect ratios of 5:1 (Bloesch and Burns 1980) were installed 1 m off the lake bottom on 8 August at the main deep site. Sedimenting particles trapped in the collectors were retrieved every 1 or 2 weeks. These samples were frozen for future electron microscopic examination and analyses of organic content, major ions, phosphorus and nitrogen content.

Halfmoon Lake froze over on 12 November 1989. Sample collection during the winter was every two weeks at the main deep site. Analyses of the water samples collected are the same as during the summer. As well as the routine samples collected, water for determination of [ $\text{Chl}_a$ ] was collected from a depth of 1 m.

## 2.2 Sample Analyses

Water and sediment sample analyses were carried out in accordance with standard analytical techniques. The specific methods of analyses are listed in Appendix B.

## 2.3 Data Analyses

Average whole-lake concentrations (except for winter [DO]) were calculated as the sum of volume-weighted discrete samples divided by total summer lake volume and are presented as means  $\pm$  1 standard error. This method enables comparison of mean summer and winter concentrations of various constituents (Barica 1977). Mean winter [DO] were calculated according to the under-ice volume of water.

The winter oxygen depletion rate was calculated as the slope of the regression line of mass of dissolved oxygen ( $\text{g O}_2/\text{m}^2$ -under ice surface area) against time (days past freeze-up). Units for this measurement are  $\text{g O}_2/\text{m}^2/\text{d}$  (Welch 1976).

## 2.4 Lake Treatment

Hydrated lime ( $\text{Ca(OH)}_2$ ) was applied to Halfmoon Lake between 8 and 17 August; no lime was applied during the weekend (12 to 13 August). 150 Tonne of  $\text{Ca(OH)}_2$  (97% pure) were ordered for the treatment; however, due to the nature of bulk transport, only 138.6 Tonne were delivered and added to the lake. The addition of this lime is equivalent to an average dosage of 70 mg/L (pure)  $\text{Ca(OH)}_2/\text{L}$  or 37.8 mg/L of calcium ( $211 \text{ g Ca}/\text{m}^2$  lake surface area). Lime



application was performed with a custom-built barge. Lime was mixed with lake water to form a slurry and applied onto the lake surface.

### 3. RESULTS

Physical data and results of chemical analyses on the water samples are found in Appendix C. In this section of the report a general overview of all parameters of interest will be given. Specific details of parameters impacted by the lime treatment (i.e. TP, Chl<sub>a</sub>, and DO) will be treated in more depth in the discussion section of the report.

#### 3.1 Open-Water

##### **3.1.1 Physical**

3.1.1.1 Temperature (Table C-1) Spring break-up occurred on 4 May 1989, and permanent thermal stratification was established by 30 May and remained throughout the summer. By 5 September 1989 the lake started to mix and was isothermal (7.6°C) by 17 October. The lake froze over on 12 November 1989.

3.1.1.2 Dissolved Oxygen (Table C-2) Dissolved oxygen profiles in Halfmoon Lake resembled those typically found in hyper-eutrophic lakes. After permanent thermal stratification was established (30 May), hypolimnetic [DO] quickly decreased and were less than 1.0 mg/L below 5 m by 13 June. The hypolimnion was essentially anoxic from 5 July until fall turnover. On the last sampling date of the open-water season in 1989 (26 October), DO saturation was 85% (mean [DO] was 9.3 mg/L) throughout the water column.

Epilimnetic [DO] was usually high (above 9 mg/L, 15 out of 18 sampling dates); the lowest value (3.65 mg/L at 0 m on 8 August) was recorded following collapse of the July algal bloom.

3.1.1.3 Light Penetration Light penetration was determined with both a light meter (Table C-3) and a Secchi disk (Table C-9). The light meter was used to define the depth of the euphotic zone (1% of subsurface penetrating irradiance). In 1989, mean  $\pm$  1 SE for the euphotic zone depth and Secchi disk depth was  $4.0 \pm 0.24$  m and  $1.21 \pm 0.13$  m, respectively.

Light penetration was greatest in the spring (May and June) and fall (September and October). Maximum (2.3 m) and minimum (0.3 m) Secchi disk depths were recorded on 19 September and 19 and 25 July, respectively. Maximum depth of the euphotic zone (based on light meter data (5.5 m) was recorded on: 16 May, 13 June, and 8 August. Minimum euphotic zone depth (1.5 m) was recorded on: 19 and 25 July and 2 August.

3.1.1.4 pH and Alkalinity (Table C-4) pH increased in the composite samples collected during the summer from 8.2 (9 May 1989) to 9.1 (2 August) and, coincident with the algae bloom crash, decreased to 8.2 by 8 August. Highest pH recorded all summer was 10.4 (Table 2 below) at the dock where the lime was being loaded onto the barge during the period of lime application. After the lime treatment was complete pH slowly decreased to 8.6 by 19 September 1989.

During thermal stratification, pH was higher in the epilimnion than in the hypolimnion as a result of photosynthesis in the epilimnion and decomposition in the hypolimnion.

Epilimnetic alkalinity decreased throughout the summer (219 mg/L  $\text{CaCO}_3$  at 0 m on 9 May, 160 mg/L  $\text{CaCO}_3$  on 6 June, 128 mg/L



CaCO<sub>3</sub> on 28 June, and back up to 173 mg/L CaCO<sub>3</sub> on 5 July and down to 114 mg/L CaCO<sub>3</sub> on 28 August). Alkalinity was dominated by bicarbonate throughout the open-water period. Application of lime reduced total alkalinity slightly; in the composite samples total alkalinity decreased from 132 mg/L CaCO<sub>3</sub> on 8 August to 114 mg/L on 28 August.

---

Table 2. pH measured at three sites during lime application

---

| Date   | Time | Beach | Dock | Other             |
|--------|------|-------|------|-------------------|
| 9 Aug  | 1530 | 8.7   | 9.4  | ----              |
|        | 1840 | 9.4   | 9.4  | ----              |
| 10 Aug | 0900 | 9.3   | 9.3  | ----              |
|        | 1400 | 9.3   | 9.4  | ----              |
|        | 2145 | ---   | 9.5  | ----              |
| 11 Aug | 0800 | 9.5   | 9.6  | ----              |
|        | 1120 | 9.6   | 9.9  | ----              |
| 14 Aug | 0900 | 9.8   | 9.5  | ----              |
|        | 2000 | 9.3   | 10.3 | ----              |
| 15 Aug | 1000 | ---   | ---  | 9.3 <sup>a</sup>  |
| 17 Aug | 0700 | ---   | 10.0 | ----              |
| 18 Aug | 0730 | ---   | 9.9  | 10.2 <sup>a</sup> |
|        | 1000 | ---   | 10.4 | 9.8 <sup>b</sup>  |

<sup>a</sup> Measured at the main site

<sup>b</sup> Measured at the north end of the lake

---

3.1.1.5 Conductivity (Table C-5) Conductivity is a measure of the total dissolved ion content of water. In Halfmoon Lake conductivity was usually highest at the bottom of the water column. At fall overturn, and up to the last sampling date (26 October), conductivity was fairly constant throughout the water column.

3.1.1.6 Color (Table C-6) The color of water is the result of light absorption and attenuation from suspended and dissolved material in water. Very "clear" water will have a color of 0 mg/L as Pt, whereas a very heavily stained body of water (eg. a bog) will have a color near 300 mg/L Pt. Mean water color of the composite samples in 1989 was  $16.3 \pm 1.10$  mg/L as Pt. The highest color (22.5 mg/L Pt) was recorded on 2 August 1989, when the algal bloom was collapsing, and probably reflected material being released from dying algal cells.

3.1.1.7 Turbidity (Table C-6) Turbidity is a measure of particulate material in water and consists of living (eg. algae and zooplankton) and non-living (eg. sediments) matter. Pure water will have a turbidity of 0.0 NTU, whereas water in a river experiencing severe spring runoff can have a turbidity in excess of 500 NTU. In 1989, mean turbidity in the composite samples was  $6.9 \pm 1.48$  NTU; maximum turbidity coincided with the mid-summer algal bloom (23.0 NTU on 19 July).

### 3.1.2 Chemical and Biological

Table 3 lists [TP], [Chl<sub>a</sub>], and [Ca] in Halfmoon Lake during the summer of 1989.

Table 3. Average whole-lake volume-weighted (VW) concentrations of TP (ug/L) and Ca (mg/L), and composite (COMP) sample (0-2.5 m) concentrations of TP and Chl<sub>a</sub>.

| Date    | Ca (VW) | TP (VW) | TP (COMP) | Chl <sub>a</sub> (COMP) |
|---------|---------|---------|-----------|-------------------------|
| May 9   | 29.0    | 93.0    | 85.7      | 27.1                    |
| 16      | 26.6    | 70.4    | 58.4      | 12.6                    |
| 25      | 30.9    | 64.9    | 64.9      | 16.7                    |
| 30      | 31.8    | 67.7    | 66.2      | 16.2                    |
| June 6  | 32.4    | 65.8    | 68.2      | 17.6                    |
| 13      | 29.5    | 46.7    | 53.1      | 11.0                    |
| 21      | 24.6    | 60.0    | 53.5      | 14.7                    |
| 28      | 28.0    | 70.6    | 59.7      | 16.9                    |
| July 5  | 25.4    | 64.9    | 66.4      | 23.7                    |
| 19      | 20.8    | 101     | 89.7      | 82.5                    |
| 25      | 18.3    | 80.4    | 80.7      | 63.2                    |
| Aug. 2  | 17.6    | 101     | 89.2      | 64.3                    |
| 8       | 16.7    | 81.9    | 65.6      | 11.7                    |
| 23      | 12.4    | 84.0    | 57.5      | 16.7                    |
| 28      | 15.3    | 94.9    | 60.9      | 11.0                    |
| Sep. 5  | ----    | -----   | 73.4      | 5.99                    |
| 19      | 15.7    | 96.3    | 94.5      | 15.5                    |
| Oct. 17 | 15.4    | 72.4    | 66.9      | 16.7                    |
| 26      | 16.7    | 70.3    | 65.5      | 13.6                    |

3.1.2.1 Total Phosphorus [TP] in the composite sample (Figure 1 and Table C-9) averaged  $69.5 \pm 2.92$  ug/L during the open-water period. [TP] ranged from 53.1 to 95.4 ug/L on 13 June and 19 September, respectively. Maximum [TP] was recorded after fall turnover and is a reflection of TP-rich hypolimnetic water mixing with epilimnetic

## HALFMOON LAKE

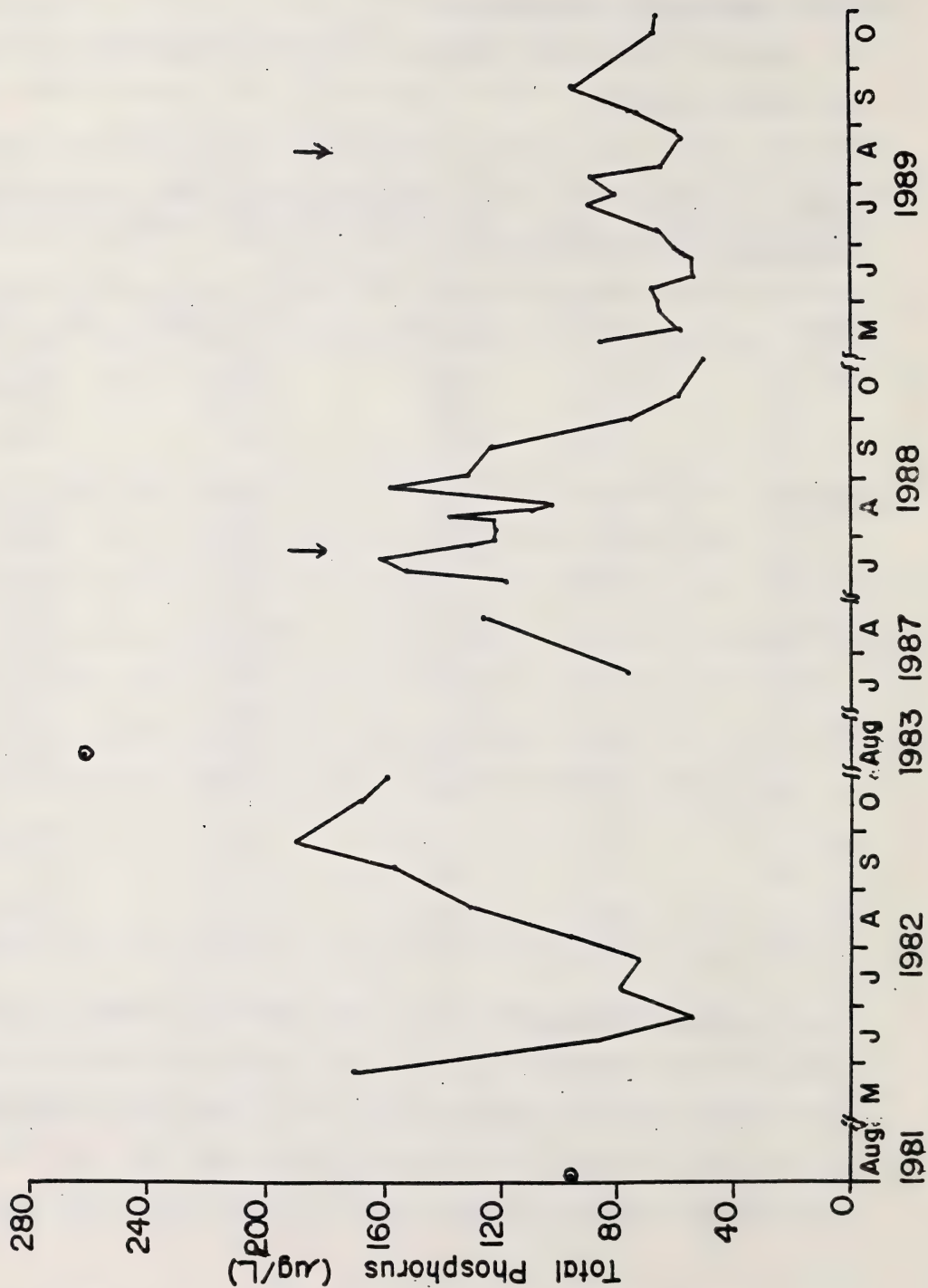


Figure 1. Total phosphorus in the composite samples from Halfmoon Lake.



## HALFMOON LAKE

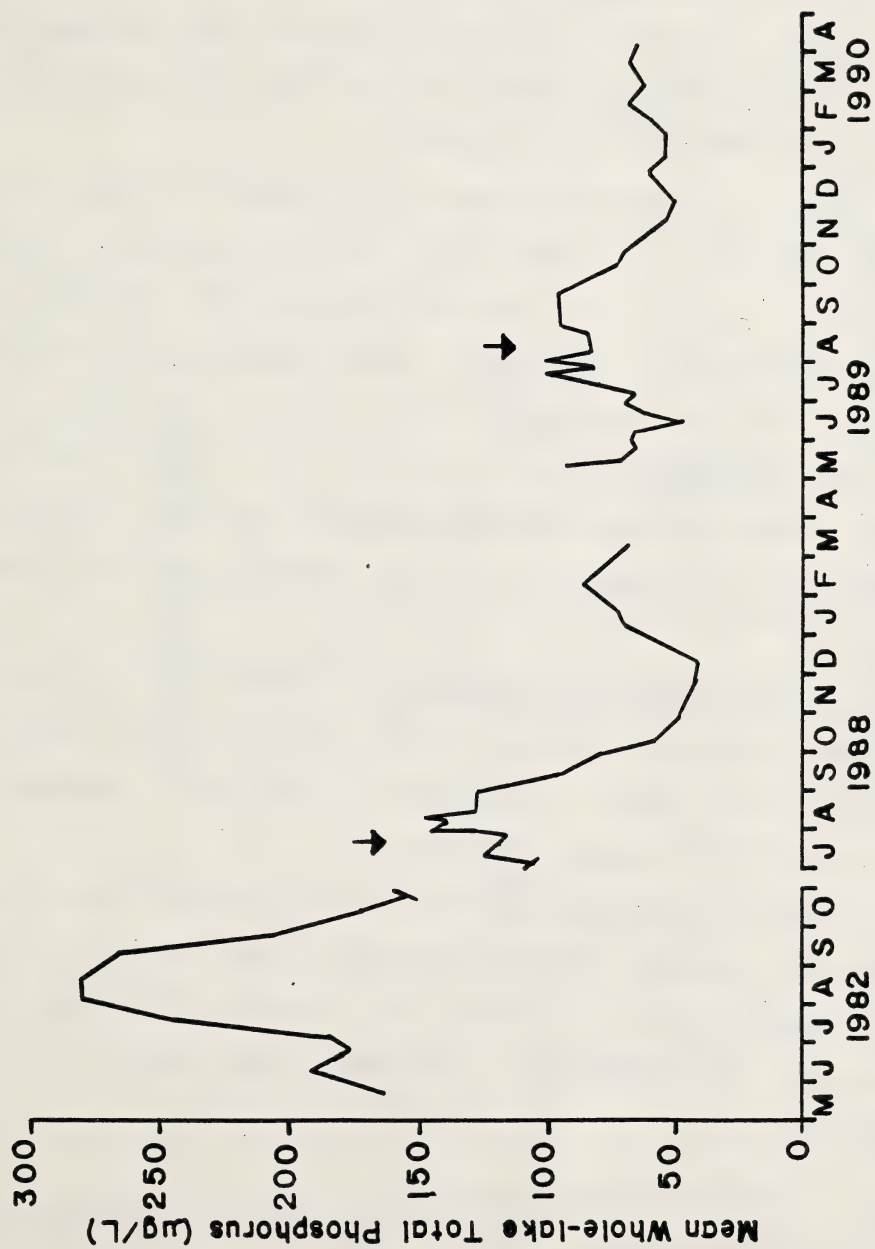


Figure 2. Whole-lake volume weighted total phosphorus in Halfmoon Lake.

water. On the last sampling date (26 October 1989) prior to freeze-up (12 November), [TP] in the composite sample was 65.5 ug/L.

[TP] in the composite samples was linked to [Chl<sub>a</sub>] during July and August; relatively high [TP] (80 to 90 ug/L) dropped quickly when the algal bloom crashed ([TP] was only 65.5 ug/L on 8 August compared to 89.2 ug/L on 2 August).

Volume-weighted whole-lake [TP] (Figure 2, Tables 3 and C-7) ranged from 46.7 (13 June) to 101 ug/L (19 July and 2 August) and averaged  $77 \pm 3.64$  ug/L. Maximum recorded [TP] occurred during the algal bloom in July and August. After spring breakup volume-weighted [TP] decreased from 93.0 (9 May) to 46.7 ug/L (13 June) and then increased during the summer. Just prior to fall overturn [TP] reached 96.3 ug/L (19 September). After fall overturn [TP] had decreased to 70.3 ug/L on the last sampling date (26 October).

3.1.2.2 Total Dissolved Phosphorus In 1989, [TDP] in the composite samples (Table C-9) averaged  $25.1 \pm 2.03$  ug/L and ranged from 17.2 (9 May) to 49.2 ug/L (19 September). After fall turnover [TDP] decreased to 25.5 ug/L (26 October).

Whole-lake volume-weighted [TDP] fluctuated more than in the composite samples, average whole-lake [TDP] was  $33.1 \pm 2.74$  ug/L and ranged from 21.6 (16 May) to 61.8 ug/L (28 August). After fall turnover, whole-lake [TDP] decreased to 28.2 ug/L on the last sampling date.

3.1.2.3 Chlorophyll a [Chl<sub>a</sub>] In the composite samples collected from the euphotic zone (Figure 3 and Table C-9) in Halfmoon Lake

## HALFMOON LAKE

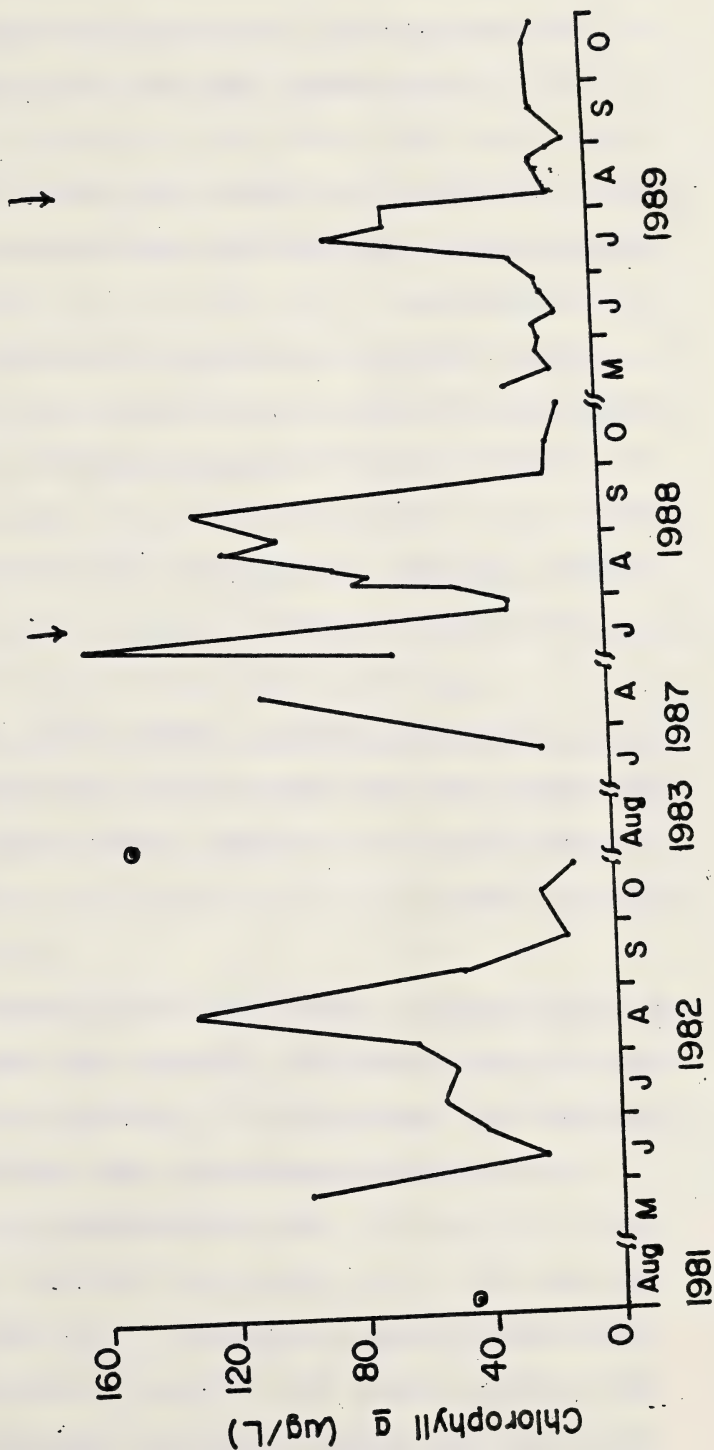


Figure 3. Chlorophyll a in the composite samples from Halfmoon Lake.

in 1989 averaged  $24.1 \pm 4.87$  ug/L and ranged from 82.5 (19 July) to 5.99 ug/L (5 September). Highest [Chl<sub>a</sub>] was measured during an algal bloom that lasted from 19 July to 2 August 1989. The algal bloom crashed prior to lime application (8 August) and [Chl<sub>a</sub>] remained relatively low for the remainder of the open-water sampling regime.

Data collected by Alberta Environment show an algal bloom developed which we did not sample; on 10 October 1989, [Chl<sub>a</sub>] of 54.9 ug/L was measured from a composite sample collected by the Water Quality Monitoring Branch (D. Trew, pers. comm.). By 17 October, our data indicate the fall bloom had subsided; [Chl<sub>a</sub>] on this date was 16.7 ug/L.

3.1.2.4 Nitrite + Nitrate (Table C-10) [NO<sub>2</sub> + NO<sub>3</sub>] fluctuated throughout the open-water period. The highest [NO<sub>2</sub> + NO<sub>3</sub>] were recorded after fall turnover (range of 200 to 229 ug/L) on 17 October 1989.

3.1.2.4 Ammonium (Table C-10) [NH<sub>4</sub><sup>+</sup>] also fluctuated throughout the sampling period in 1989. Highest concentrations were always in the hypolimnion; maximum [NH<sub>4</sub><sup>+</sup>] recorded was in excess of 6,000 ug/L at 7.5 m on 28 August. Relatively high epilimnetic [NH<sub>4</sub><sup>+</sup>] on 2 and 8 August (108 and 510 ug/L, respectively, in the composite samples) corresponded to the algal bloom collapse in early August. After fall turnover [NH<sub>4</sub><sup>+</sup>] increased in the upper waters; on 19 September 1989, [NH<sub>4</sub><sup>+</sup>] ranged from 634 to 675 ug/L throughout the water column. By 17 October [NH<sub>4</sub><sup>+</sup>] had decreased to 134 to 191 ug/L.



throughout the water column. This decrease corresponds to the increase in  $[\text{NO}_2 + \text{NO}_3]$  noted above for the same dates.

3.1.2.6 Na, K, and Mg Concentrations of Na, K, and Mg (Table C-11) were relatively constant throughout the sampling period in 1989. These parameters averaged:  $20.7 \pm 0.51$ ,  $14.0 \pm 0.25$ , and  $11.3 \pm 0.44$  mg/L, respectively. Only Mg displayed consistent increases in concentration throughout the water column; slightly higher values were usually observed in the deeper waters.

3.1.2.7 Calcium In 1989, mean whole-lake volume weighted [Ca] (Figure 4 and Tables 3 and C-11) were similar to the mean composite (0 to 2.5 m) samples ( $22.6 \pm 1.58$  and  $21.2 \pm 1.92$  mg/L, respectively). [Ca] displayed tremendous spatial and temporal variation throughout the water column; highest concentrations were always detected in the hypolimnion. Maximum [Ca] recorded was 40.5 mg/L at 7.5 m on 28 August and minimum [Ca] recorded was 8.14 mg/L at the surface on 23 August.

Although the lime treatment added 37.8 mg/L of Ca to the lake; whole-lake volume-weighted [Ca] actually decreased 4.3 mg/L after all of the was added (from 16.7 mg/L on 8 August to 12.4 mg/L on 23 August). By 26 October whole-lake volume-weighted [Ca] had increased to pre-lime application values.

3.1.2.8 Phytoplankton (Table C-12) Changes in the phytoplankton population dynamics in Halfmoon Lake in 1989 are illustrated in Figure 5. Total algal biovolume ( $\mu\text{m}^3/\text{ml}$ ) followed the pattern

## HALFMOON LAKE

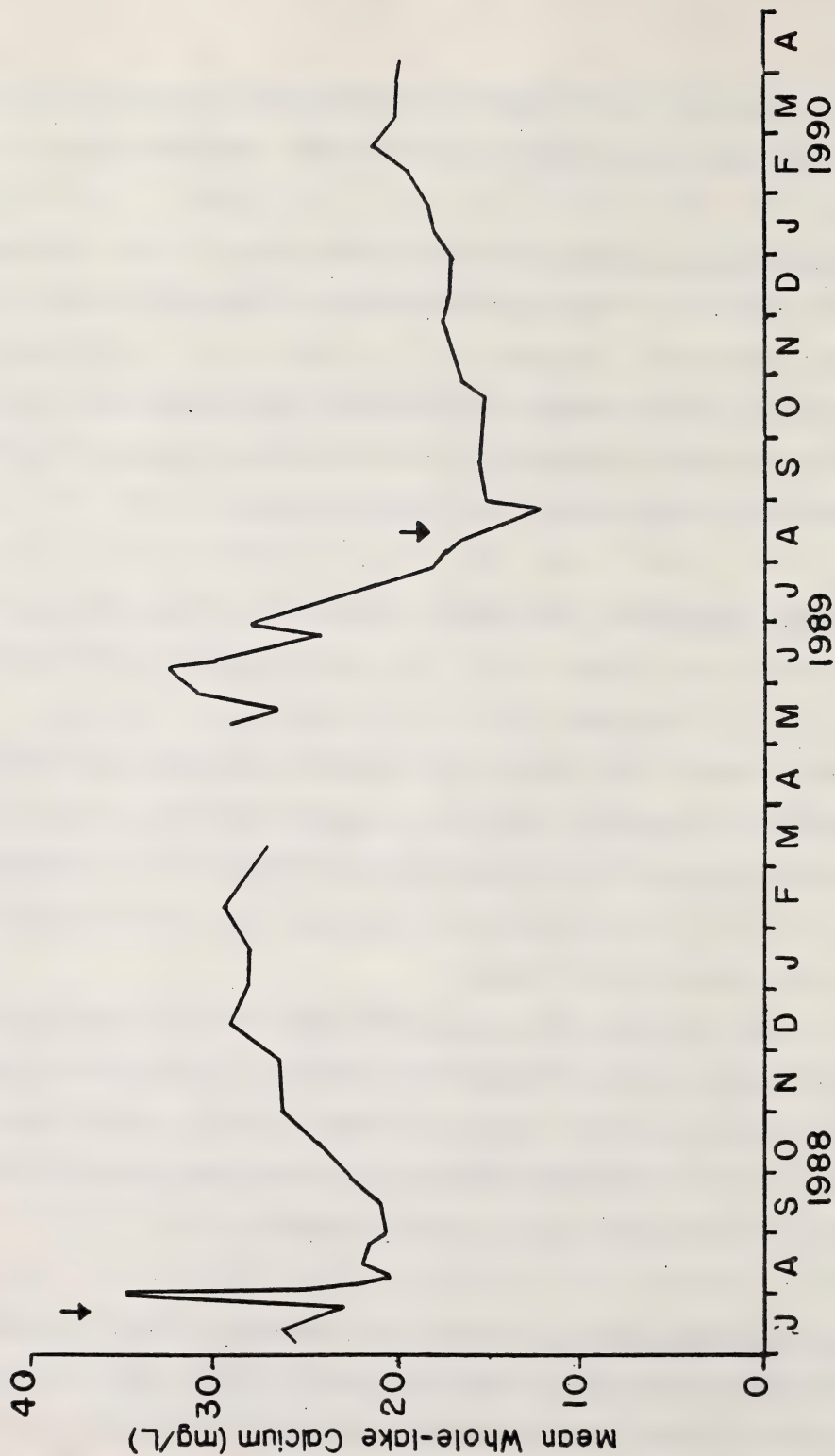


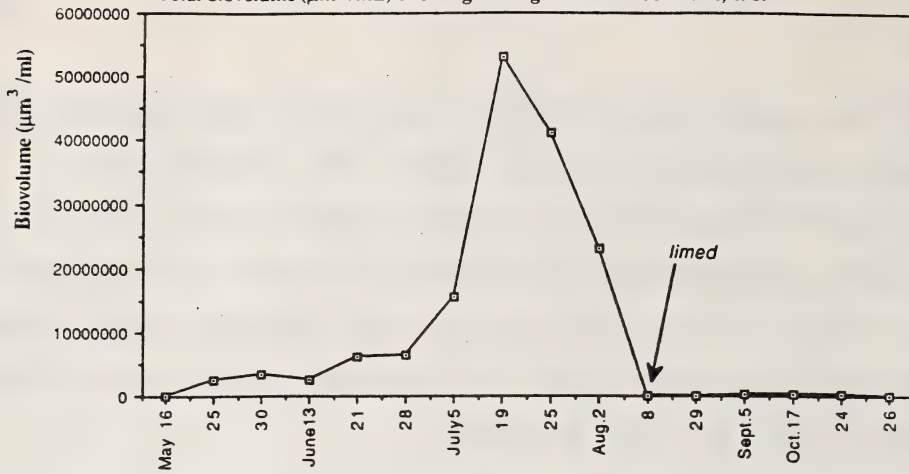
Figure 4. Whole-lake volume weighted calcium concentration in Halfmoon Lake.

observed with total [Chl<sub>a</sub>] throughout the year; maximum biovolume was observed during the July algal bloom. The phytoplankton population was dominated by blue-green algae up to the time the bloom crashed; *Oscillatoria limnetica* and *Anabaena planctonica* were the most abundant of the blue-green algae. After the algal bloom subsided (which coincided with the lime application), green algae dominated the phytoplankton population.

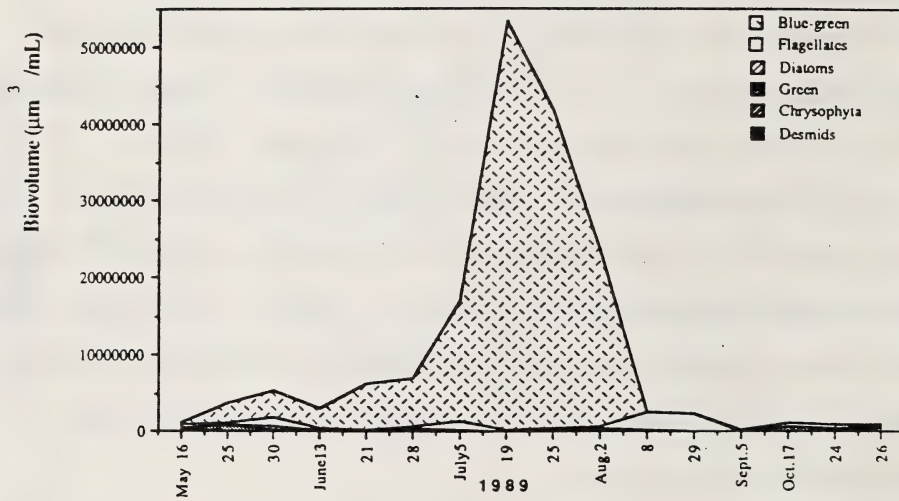
3.1.2.9 Sediments Analyses of the sediment samples (Table C-13) revealed a significant increase in the calcium content and the calcium:phosphorus ratio in the surface sediments. These increases are a result of the lime applications in 1988 and 1989 .

Analyses of the porewater (Table C-13) showed relatively low concentrations of DO, soluble reactive phosphorus, and  $\text{Fe}^{+2}$  in both the sediments and the superstitial water. However, porewater [SRP] was 7 to 8 times greater than that measured in the superstitial water indicating the potential for phosphorus flux from the sediments to the water column.

Total biovolume ( $\mu\text{m}^3/\text{mL}$ ) of blue-green algae in Halfmoon Lake, 1989



Changes of Phytoplankton Biovolume in Halfmoon L., 1989



Changes of other Phytoplankton in Halfmoon L., 1989

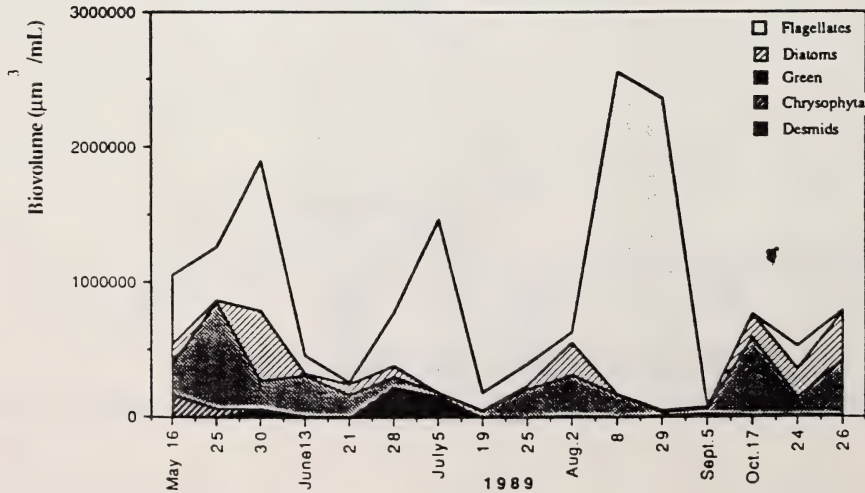


Figure 5. Phytoplankton species composition in Halfmoon Lake.



### 3.2 Ice-Cover

Physical and chemical data collected in Halfmoon Lake under ice-cover in 1989-90 are found in Appendix C (Tables C-14 to C-16). This section of the report focuses on the main parameters of interest ([DO], [TP], [Chl<sub>a</sub>], and [Ca]) for the winter of 1989-90.

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Table 4. Mean volume-weighted concentrations of DO, TP, and Ca for the winter of 1989-90. [Chl<sub>a</sub>] was determined from samples collected at 1 m.

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| Date   | DO (mg/L) <sup>a</sup> | TP (ug/L) <sup>b</sup> | Ca (mg/L) <sup>b</sup> | Chl <sub>a</sub> (ug/L) |
|--------|------------------------|------------------------|------------------------|-------------------------|
| Nov 27 | 10.19                  | 53.5                   | 17.6                   | 4.51                    |
| Dec 7  | 9.16                   | 50.4                   | 17.4                   | 2.51                    |
| 28     | 7.05                   | 60.1                   | 17.2                   | 1.19                    |
| Jan 11 | 6.38                   | 54.3                   | 18.3                   | 1.85                    |
| 25     | 5.82                   | 54.1                   | 18.6                   | 10.2                    |
| Feb 8  | 4.73                   | 58.6                   | 19.6                   | 5.33                    |
| 21     | 3.00                   | 68.0                   | 21.5                   | 5.29                    |
| Mar 5  | 2.27                   | 62.6                   | 20.4                   | 3.48                    |
| 19     | 2.63                   | 67.7                   | 20.3                   | 36.7                    |
| Apr 3  | 9.07                   | 65.7                   | 20.1                   | ----                    |

<sup>a</sup> based on the lake volume at time of sampling.

<sup>b</sup> based on the summer lake volume.

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#### **3.2.1 Dissolved Oxygen**

[DO] throughout the water column in the winter of 1989-90 are high relative to historic levels. Babin (1984) studied the oxygen regime in Halfmoon Lake during the winter of 1982-83 and found that by late January 1983, the lake was essentially anoxic. In contrast to the previous study, the lowest mean [DO] (2.27 mg/L) during 1989-90 was measured on 5 March 1990. By 19 March the [DO] had increased to 2.63 mg/L and continued increasing until 3 April 1990, when the mean [DO] reached 9.07 mg/L.

In 1989-90 the winter oxygen depletion rate (WODR) for the period 27 November to 11 January was  $0.377 \text{ g O}_2/\text{m}^2/\text{d}$ ; while in 1982-83 the WODR for approximately the same period (18 November to 9 January) was  $0.481 \text{ g O}_2/\text{m}^2/\text{d}$ .

### 3.2.2 Total Phosphorus

Average whole-lake [TP] (corrected for the summer lake volume) measured during the winter of 1989-90 increased from 53.5 (27 November) to 65.9  $\mu\text{g/L}$  (3 April). These values are lower than [TP] measured on the last sampling date prior to freeze-up (70.3  $\mu\text{g/L}$  on 26 October 1989). There was a significant buildup of TP in the bottom water overlaying the sediments in Halfmoon Lake during the winter when [DO] was low; maximum [TP] measured was 284  $\mu\text{g/L}$  at 8 m on 5 March 1990.

### 3.2.3 Calcium

Average whole-lake [Ca] (corrected for the summer lake volume) steadily increased from 17.6 (27 November 1989) to 20.1  $\text{mg/L}$  (3 April). This increase in [Ca] is a result of dissolution of  $\text{CaCO}_3$  from the sediments and is similar to previous experience in another lime-treated lake in Alberta (Figure Eight Lake; Prepas, Murphy, and Babin 1988).

### 3.2.4 Chlorophyll a

[Chla] under ice-cover was relatively low throughout the winter. A small bloom (10.3  $\mu\text{g/L}$ ) was recorded on 25 January and [Chla] thereafter decreased to 3.48  $\mu\text{g/L}$  on 5 March. By 19 March

[Chla] had increased (36.7 ug/L) and resulted in a significant increase in [DO] at the 1 m depth; [DO] at 1 m increased from 4.83 to 10.9 mg/L from 5 to 19 March, respectively.

## 4. WATER QUALITY COMPARISON WITH OTHER YEARS

Table 5. Historical [TP], [Chla], and WODR in Halfmoon Lake

| YEAR              | DATE             | [TP] <sup>a</sup><br>(ug/L) | [Chla] <sup>a</sup><br>(ug/L) | WODR<br>(g O <sub>2</sub> /m <sup>2</sup> /d) |
|-------------------|------------------|-----------------------------|-------------------------------|---|
| 1981 <sup>b</sup> | August 4         | 96                          | 46                            | -----   |
| 1982 <sup>c</sup> | July             | 75                          | 52                            | -----   |
|                   | August           | 113                         | 96                            | -----   |
|                   | September        | 173                         | 30                            | -----   |
|                   | October          | 162                         | 16                            | -----   |
| 1982 <sup>d</sup> | Nov 18 to Jan 9  | ---                         | ---                           | 0.481   |
|                   | March 10         | 194*                        | ---                           | -----   |
| 1983 <sup>e</sup> | August 8         | 260                         | 148                           | -----   |
| 1987 <sup>e</sup> | July 22          | 76                          | 20                            | -----   |
|                   | August 17        | 126                         | 107                           | -----   |
| 1988 <sup>e</sup> | July 25          | 143                         | 41                            | -----   |
|                   | August 2         | 106                         | 55                            | -----   |
|                   | September 13     | 107                         | 95                            | -----   |
| 1988 <sup>f</sup> | July             | 138                         | 91                            | -----   |
|                   | August           | 127                         | 84                            | -----   |
|                   | September        | 99                          | 70                            | -----   |
|                   | October          | 54                          | 12                            | -----   |
|                   | Nov 26 to Jan 19 | ---                         | ---                           | 0.456   |
|                   | Nov 26 to Mar 9  | ---                         | ---                           | 0.416   |
|                   | March 9          | 68.9*                       | ---                           | -----   |
| 1989 <sup>g</sup> | May              | 69                          | 18                            | -----   |
|                   | June             | 59                          | 15                            | -----   |
|                   | July             | 79                          | 56                            | -----   |
|                   | August           | 68                          | 26                            | -----   |
|                   | September        | 84                          | 11                            | -----   |
|                   | October          | 66                          | 15                            | -----   |
|                   | Nov 27 to Jan 11 | ---                         | ---                           | 0.377   |
|                   | Nov 27 to Jan 25 | ---                         | ---                           | 0.332   |
|                   | Nov 27 to Mar 5  | ---                         | ---                           | 0.347   |
|                   | March 5          | 62.6*                       | ---                           | -----   |

<sup>a</sup> Euphotic zone composite samples<sup>b</sup> Prepas and Trew (1983)<sup>c</sup> Riley (1983), monthly averages<sup>d</sup> Babin (1984)<sup>e</sup> Alberta Environment, unpublished data<sup>f</sup> Prepas and Babin (1989) monthly averages based on weekly averages<sup>g</sup> This study

\* Mean concentration (total mass divided by summer volume)



In this section of the report, data ([TP], [Chl<sub>a</sub>], and [Ca]) collected during 1989-90 will be compared with data collected in previous years.

#### 4.1 Total Phosphorus

The long-term [TP] trend in the composite and the whole-lake volume-weighted samples are illustrated in Figures 1 and 2, respectively. Mean monthly [TP] was lower in every month during 1989 than recorded previously, except for July (4 ug/L lower in 1982) and October (12 ug/L lower in 1988). Furthermore, maximum [TP] in the composite sample (95.4 ug/L) was much lower than previous maximum concentrations recorded (190 and 161 ug/L in 1982 and 1988, respectively).

Mean and maximum whole-lake [TP] in 1989 (77 and 101 ug/L, respectively) were significantly lower than in 1982 (211 and 280 ug/L) and 1988 (114 and 149 ug/L). This difference implies reduced phosphorus loading from the sediments and is consistent with the effects of lime additions to Figure Eight Lake and to the drinking water dugouts in Alberta. In 1982, internal phosphorus loading accounted for 97% of the TP loading in Halfmoon Lake (calculated from data in Riley (1983)). Clearly, a change in the phosphorus dynamics in Halfmoon Lake has occurred. We suggest that this change is a result of increased binding of phosphorus by calcium as hydroxyapatite in the bottom sediments.

#### 4.2 Chlorophyll a

Figure 3 illustrates [Chl<sub>a</sub>] in composite samples collected from 1981 to 1989. Mean and maximum [Chl<sub>a</sub>] in 1989 (24.1 and 82.5 ug/L, respectively) were much lower than in 1988 (68.9 and 161 ug/L) and 1982 (50 and 129 ug/L). The reduced [Chl<sub>a</sub>] in Halfmoon Lake during 1989 can be attributed to reduced [TP] in the water.

#### 4.4 Calcium

Mean whole-lake volume-weighted [Ca] (Figure 4) in Halfmoon Lake was slightly lower in 1989 than in 1988 (22.6 and 23.8 mg/L respectively). One result of the stronger lime treatment in 1989 was that whole-lake [Ca] decreased to the lowest value ever recorded (12.4 mg/L) even though 37.8 mg/L of Ca was added to the lake. The reason for the decrease in [Ca] was that the lake was super saturated with calcite ( $\text{CaCO}_3$ ) before the lime treatment. With the addition of 37.8 mg/L of Ca (as  $\text{Ca}(\text{OH})_2$ ) more calcite was formed (by combining with dissolved  $\text{CO}_2$ ) so that there was an immediate precipitation of excess  $\text{CaCO}_3$  and with it excess Ca.

#### 4.4 Oxygen Under Ice-Cover

The oxygen regime in Halfmoon Lake under ice-cover in 1989-90 was greatly improved over 1988-89 and 1982-83. The winter oxygen depletion rate (WODR) in 1989-90 was 22% lower than in 1982-83 and 17% lower than in 1988-89.

The magnitude of WODR are controlled by two variables: morphometry (i.e. mean depth) and productivity of the lake (i.e. [TP] or [Chl<sub>a</sub>]) (Babin and Prepas 1985). Since the morphometry of

the lake hasn't changed the decreases in WODR are probably related to decreased lake productivity.

Another aspect of improved [DO] in Halfmoon Lake during the winter of 1989-90 is the relatively high [DO] at freeze-up relative to previous years. DO saturation at freeze-up in 1982, 1988, and 1989 were: 67, 77 and 85% respectively. DO saturation at freeze-up is dependent upon the length of time of fall circulation and the oxygen demand of the lake during this circulation period. The length of fall circulation was essentially the same for all three years studied. The oxygen demand in the lake during fall turnover is a function of the amount of biological and chemical oxygen demand (BOD and COD, respectively) in the water column and sediments. BOD and COD are formed in lakes as a result of productivity; the greater the productivity in a lake, the greater the oxygen demand in the lake. Productivity (as measured by [TP]) was lowest in 1989, followed by 1988 and then 1982; hence BOD and COD during fall turnover probably was lowest in 1989, followed by 1988, and 1982.

Thus, increased DO saturation at freeze-up and decreased WODR combined to significantly improve the DO regime under ice-cover in 1989-90 relative to historic values.

## 5. EFFECTS OF LIME TREATMENT IN HALFMOON LAKE

The effectiveness of the lime treatments in Halfmoon Lake can be determined by comparing historical information from Halfmoon Lake to the data collected in this (1989-90) and subsequent years.

During the open-water season of 1989, the two main indices of eutrophication (i.e. [TP] and [Chl<sub>a</sub>]) were significantly lower than historical records. Although there was a mid-summer algal bloom (82.5 ug/L [Chl<sub>a</sub>] on 19 July 1989), mean and Maximum [Chl<sub>a</sub>] and [TP] in 1989 were lower than those recorded in 1982 and 1988. Thus, it appears the lime treatments in 1988 and 1989 decreased the amount of TP in the water column and, consequently, decreased the amount of algal biomass in Halfmoon Lake.

Oxygen depletion under ice-cover is related to the productivity of lakes (Babin and Prepas 1985). A decrease in lake productivity (i.e. a decrease in [TP] or [Chl<sub>a</sub>]) will result in a decrease in the winter oxygen depletion rate of the lake. The WODR in Halfmoon Lake in 1989-90 was lower than in 1988-89 and 1982-83. This decreased WODR is probably due to decreased productivity in the lake as noted above.

Associated with the above improvement in DO, caused by lime treatment, will be a further reduction of TP in the lake. Since the DO content of the lake under ice-cover is improved, the amount of phosphorus released from the sediments to the water column will be decreased relative to previous years. Hence less phosphorus will be available for phytoplankton growth in the spring resulting in lower algal biomass in the summer.



We believe that phosphorus availability in Halfmoon Lake is inversely proportional to the calcium to phosphorus ratio (Ca:TP) in the sediments. By adding lime, the Ca:TP increases in the bottom sediments, hence the availability of sediment bound phosphorus is decreased and open-water [TP] will decrease.

By intensive monitoring of Halfmoon Lake in the future, and addition of sufficient lime to maintain relatively high Ca:TP in the sediments, we will be able to determine the long-term effects of lime additions to lakes as a method of controlling algal productivity.

## 6. FUTURE WORK

Sampling of Halfmoon Lake should be continued as an integral part of the liming program undertaken in cooperation with the Alberta Environmental Center. Only through intensive long-term monitoring of this and other treated and control lakes will the long-term effects of lime application as a means of controlling algal biomass be determined.

The Halfmoon Lake program will be integrated into the four to five year program to be coordinated with Drs. John Hardy and Sherman Weaver at the Alberta Environmental Center in Vegreville.

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## APPENDIX A

### Lake Liming to Enhance Water Quality Prepared by E.E. Prepas and P.J. Curtis

#### General Introduction

The nutrient phosphorus controls the amount and production rate of algae in most freshwaters (Schindler, 1974). Recently compiled data for lakes in Alberta indicated that more than half of the approximately 100 lakes surveyed contained very high concentrations of algae (eutrophic), and that one quarter of those surveyed contained extremely high concentrations of algae (hyper-eutrophic). In western Canada, excessive growth of algae, caused by high phosphorus concentrations, are unsightly to recreational users, produce unpleasant odors and tastes, and cause winter- and summer-kill of fishes when bacteria that decompose algae consume all available oxygen. In addition, special weather and nutrient conditions apparently cause algae common to western Canada (species of blue-green algae) to produce neuro- and hepato-toxins in quantities that are dangerous or lethal for humans, livestock and wildlife (Carmicheal and Gorham, 1981). While the causes of toxic blooms of blue green algae are unknown, current hypotheses in the scientific literature suggest that undesirable blue-green algae thrive when concentrations of available phosphorus are high (Trimbee and Prepas, 1987; Smith, 1986).

In an attempt to reduce excessive algal growth, phosphorus abatement programmes been implemented for many freshwaters. However these programmes have only been uniformly successful



where phosphorus inputs are from easily regulated point sources, such as municipal or lakeshore septic tanks (De Pinto et al., 1986; Dillon et al., 1978). The case in much of western Canada is quite different. Supplies of phosphorus to lakes are mainly from phosphorus-rich soils, therefore it is not feasible to limit phosphorus inputs. In many of the hardwater lakes, the problem is exacerbated by efficient recycling of phosphorus so that phosphorus inputs can be available to algae for up to twenty years before being finally buried permanently in sediments (calculated from Riley and Prepas, 1984). Consequently, up to 95% of algal production can be supported by internal recycling with as little as 5% from external loading.

Most current techniques for reducing concentrations of phosphorus within lakes are either expensive or system specific. For example, withdrawal of nutrient rich bottom waters before they contact the less nutrient-rich surface waters is impractical because most lakes in Alberta are too shallow and, for those that are deep enough, the volumes of water removed are too large to be replaced by precipitation and runoff in the water-poor regions of western Canada. Dredging, thick lake sediments (up to 13 m) is prohibitively expensive. Addition of alum (aluminum sulfate) binds phosphorus in sediments, but aluminum is toxic to both vertebrates and invertebrates (review in Cooke et al., 1986), and alum is strongly acidic and very expensive (Cdn.\$450/tonne). Addition of fly ash to lakes (from coal burning) to bind phosphorus in sediments, while inexpensive, introduces a host of

toxic trace metals that can be leached into water (e.g. Theis and Richter, 1979).

Techniques for directly reducing the abundance of algae are not suited to western hardwater lakes. For example, toxic herbicides like copper sulfate (now discontinued for use in Alberta lakes) frequently produce temporary suppression of algae and can be followed by bursts in growth of algae to levels higher than pre-treatment (rebound effect; Hanson and Stephan, 1984). Suppression of algae by food web manipulations (enhancing the populations of algal consumers) can reduce abundances of algae and enhance water quality for a few years in some lakes (Shapiro and Wright, 1984), but the response is variable and probably depends on the system manipulated (McQueen et al., 1986). Given that western hardwater lakes support very high concentrations of algae that are commonly deemed inedible by consumers, it is not likely that food web manipulation will reduce algal abundance.

Recent pilot experiments indicated that addition of lime to western hardwater lakes holds great promise for reducing concentrations of phosphorus and algae. Addition of lime to lakes mimics a natural phenomenon that occurs naturally in many lakes in the midwestern United States where lime (calcium carbonate) precipitates seasonally as surface waters warm and become supersaturated (eg. Vanderploeg et al., 1987). The amounts of lime precipitated depend on the input rates and concentrations of calcium and carbonate (inorganic carbon) and pH of the water.

When large amounts of calcium carbonate precipitate (events called whittings), concentrations of phosphorus and abundances of algae have been observed to decrease, presumably due to formation of insoluble calcium-phosphorus mineral (hydroxyapatite; Avnimelech, 1980; Murphy et al., 1983) that sequesters phosphorus and makes it unavailable to algae. For this reason lime is added routinely to waste-water in order to reduce concentrations of phosphorus in effluent (Shannon, 1980).

Lime has also been added safely to softwater lakes by fisheries scientists and managers for over twenty years to enhance or rehabilitate fish habitats (Fraser et al., 1982). In contrast to hardwater lakes, lime added to softwater lakes dissolves and typically increases the pH of water. Over 600 lakes in Scandinavia have been limed to save or restore habitat for fisheries threatened with local extinction by lake acidification from acidic rain (Olem et al., 1990). Highly opaque, brown water lakes in Wisconsin have also been limed to enhance optical transparency and hence sport fisheries, by precipitating offensive humic material with calcium (Stross and Hasler, 1960).

In Alberta, recent pilot experiments undertaken in two hardwater lakes to test the efficacy of lime additions to induce large whittings for reducing concentrations of phosphorus and abundances of algae (Prepas et al., in press; Prepas et al., 1990). While the treated lakes were at or slightly above



saturation for lime (calcium carbonate), whittings did not occur naturally because supplies of calcium and carbonate from the watershed were too low. Added lime precipitated rapidly because lake waters were already saturated with lime. In the months following lime addition and in the next year, concentrations of phosphorus and algae in the treated lakes were statistically lower than had been measured in previous years (Prepas et al., in press; Prepas et al., 1990). The appearance of lake water changed from pea-soup to crystal clear. Furthermore, low concentrations of phosphorus and algae in subsequent years suggested that lime in the lake sediments was effectively intercepting phosphorus before it was recycled. Similar results were obtained when lime was added to small drinking water dugouts (Murphy et al., in press).

### Proposal

By invitation of and cooperation with Alberta Environment, we propose to test the effectiveness of lime addition (in the form of calcium carbonates or hydroxides) to lakes as a means of disrupting cyclic release of phosphorus from sediments, and thereby increasing the quality of lake water for recreation and drinking. Our experimental approach is three pronged. Firstly, laboratory experiments will be conducted to determine the effect of natural variables like pH and ionic strength on the binding capacity of lime (calcite) for phosphorus. This knowledge will be used to predict the lime dosages for desired levels of water quality. Secondly, controlled whole-lake experiments will be



conducted to separate interannual variation from treatment effects and to test predictions from laboratory-based model simulations of nutrient recycling. Thirdly, lime treatments and monitoring of lakes previously limed will be continued in order to assess long-term direct and indirect effects on ecosystem structure and function that may only be detected after a few lifespans of key members of the food web (eg. Schindler et al., 1990).

### Hypothesis Testing and Design Goals

We propose to test the following scientific hypotheses.

Hypothesis 1) Artificially enhanced calcium loadings to sediments will reduce phosphorus recycling from sediments of hardwater lakes.

Corollary: The abundance of calcium (as carbonates) relative to potentially recycled phosphorus in sediments regulates the amount of phosphorus recycled from sediments by formation of hydroxyapatite.

Hypothesis 2) Given 1, then inhibited recycling of phosphorus from sediments will directly reduce concentrations and biomass of algae.

Hypothesis 3) Given 1 and 2, then hardwater lakes most responsive to lake liming treatment will be those in regions that supply large amounts of phosphorus to lakes and relatively small amounts of materials that bind phosphorus in sediments (calcium, Fe, Al). Restated, the most responsive lakes to lake liming will be those

with low ratios of (calcium+Fe+Al)/phosphorus in sediments.

Hypothesis 4) Inhibited phosphorus recycling will increase the availability of nitrogen relative to phosphorus so that phytoplankton communities will shift from blue-green dominated to more desirable green algae.

Hypothesis 5) Reduced phytoplankton concentrations and resultant increased light penetration through lake water will not enhance abundances of rooted aquatic plants because the availability of phosphorus from sediments will limit macrophyte biomass.

The relative cost effectiveness of the following variables will be determined in both laboratory and field simulations.

- 1) Application of two different forms of lime a) fine-ground calcium carbonate and b) microcrystalline calcium carbonate precipitated in situ (by combination of calcium hydroxide with hydrated atmospheric carbon dioxide).
- 2) The dependence of the response to treatment on the time of application (season and temperature).
- 3) Frequency of treatment required for desired water quality.
- 4) Criteria for predicting the effectiveness of liming in lakes with different chemistry and hydrology.

#### Rationale

Lime-induced changes in the water quality of hardwater lakes are probably linked to the capacity of the calcium in sediments to bind phosphorus and the amounts of phosphorus that is potentially recycled. We predict that the capacity of sediments to bind phosphorus will increase with increasing concentrations

of calcium relative to phosphorus (calcium/phosphorus) in sediments, and that phosphorus recycling from sediments should decrease. This is in accord with observations that: (1) where calcium/phosphorus ratios are high in unmanipulated lakes (Alberta) (e.g. Narrow Lake (calcium/phosphorus = 40) concentrations of phosphorus and algae are lower than in lakes with relatively low calcium/phosphorus (e.g. Figure Eight Lake before liming (calcium/phosphorus = 10; E.E. Prepas, unpublished data), and (2) artificially enhanced calcium concentrations in the surface sediments of Figure Eight Lake appeared to inhibit phosphorus recycling from sediments (Prepas et al., in press).

## Experimental Design and Work Plan

### Laboratory Experiments

Kinetic experiments on phosphorus removal from water by freshly precipitated calcite (from calcium hydroxide, similar to that expected to form in lakes that are limed with calcium hydroxide) will be conducted to estimate the capacity of added lime to bind phosphorus. It is expected that phosphorus binding capacity will be regulated by surface complexation and precipitation of phosphate on calcite. Diffusion of phosphate from water into the solid solution calcium-carbonate-phosphorus will probably be too slow to bind phosphorus that could be recycled to biota in days. Because commercially pulverized limestone (calcite) is much less expensive (Cdn.\$10/tonne) than calcium hydroxide (Cdn.\$100/tonne) and it is easier to apply to lakes, we propose to conduct laboratory experiments to compare the short-term specific binding capacity of pulverized limestone to that of calcite precipitated in situ in a cost benefit study.

### Experimental Lakes

Two pairs of small hardwater lakes (20 to 100 ha) in the Athabasca parkland ecotome (one experimental and one reference lake) will be selected from lakes sampled in the summer of 1986 and again under-ice during the winter 1990. Pairs of lakes will be selected from observed apparent binding capacity of sediments for phosphorus; one pair with low binding capacity and one with



moderate binding capacity. One lake from each pair will be treated with approximately 3.5 tonnes of lime (as calcium hydroxide) per hectare and the manipulated lake will serve as a reference. The lime dosage is equivalent to between fifty years and 150 years worth of natural calcium accumulation (estimated from sediment accumulation rates in Turner and Delorme, (1989) and from calcium content of sediments (Curtis unpubl. data)). Treatment lakes and reference lakes will be monitored for a full year prior to manipulation in order to assess the pretreatment characteristics of experimental lakes, and to establish similarities and possible differences between treatment and reference lakes. These controlled experiments will be conducted to test mechanistic hypotheses regarding 1) nutrient retention in sediments, 2) functional response of algae, macrophytes and other biota to lake treatment, and 3) effectiveness of liming in lakes with different characteristics of chemical loading (proportions of phosphorus relative to phosphorus binding-capacity). The proposed controlled experimental manipulation is essential to separate treatment effects from natural variation like inter-annual variation in climate or hydrology. Manipulation of the two classes of lakes is important for establishing the calcium-dependent mechanism of phosphorus-binding in sediments, and for establishing criteria for the cost benefit of treatment.

## Long-term Study Lakes

We further propose that Figure Eight and Halfmoon lakes will continue to be limed every second year to evaluate general effectiveness and impact of lake liming. The long-term record will be valuable for assessing possible shifts in ecosystem form or function and time lags for those shifts. In particular we are interested to determine whether repeated lime treatments will inhibit algal blooms to the point where winterkills of fishes (death from hypoxia due to oxygen consumption by bacteria that decompose algae and other organic materials under ice) can be reduced or eliminated. Secondly, we propose to monitor the composition of algae in the phytoplankton to determine whether liming will change undesirable blue-green algal assemblages into desirable green algal assemblages.

## Form of Lime Used

Calcium hydroxide will be used in all of the proposed lime treatments, because experiments in drinking water dugouts indicated that it was more effective than pulverized calcium carbonate for reducing concentrations of phosphorus and algae. The discrepancy between treatments has not been satisfactorily resolved, but it is likely that the effectiveness of calcium hydroxide is due to the extremely small size of the crystals precipitated from lake water compared to pulverized calcium carbonate. Because pulverized calcium carbonate is cheaper

(1/10) and safer to handle experiments will be conducted to assess cost benefits of calcium carbonate use as described in "Laboratory Experiments".

#### Lake Sampling.

Water and biota from all of the lakes will be sampled for the duration of the project, a period of at least 4 years. Concentrations of phosphorus, phosphorus-binding materials, and algae will be measured in biweekly water samples and in sediments of the study lakes by techniques described in Prepas et al., (in press). Fluxes of phosphorus and phosphorus-binding materials will be measured in sediment traps (gross) and  $^{210}\text{Pb}$  dated sediment cores (net; Krishnaswami and Lal, 1978) similar to techniques described by Curtis (1990)), and calculated from concentration profiles in lake sediments (Hesslein, 1976) and changes in the mass present in the water column. It is anticipated that 3 years of post treatment monitoring in the study lakes will be sufficient to estimate the rate of recovery to pretreatment steady state conditions, even if the lakes have not recovered completely.

The response of planktonic and rooted aquatic plants to short-term direct effects of lime application and of long-term indirect effects on growth and species composition by lime-altered phosphorus availability will be monitored. Phytoplankton concentration will be approximated regularly by measuring the

concentrations of algal pigments. Species composition of the phytoplankton will be enumerated in composite samples collected from the euphotic zone of the study lakes.

Rooted aquatic plants will be monitored in all study lakes by sampling in mid-August (the period of peak macrophyte abundance) of each year. Areal abundance of aquatic macrophytes will be estimated by harvesting plants from six fixed sites in each lake (Prepas et al., in press). On each visit, a line transect will be established perpendicular to shore at each site, extending from the shoreline to the maximum depth of macrophyte colonization. SCUBA divers will harvest plant shoots in triplicate from within  $0.25 \text{ m}^2$  quadrats placed at 1-m depth intervals along the transect line. Plants will be enumerated and the contents of nutrients analyzed by standard limnological techniques.

As a first step towards determining the impact of lime on nutrient availability and aquatic weed growth, laboratory experiments will be undertaken in which plants will be grown in tanks containing natural lake sediments to which calcium carbonate or calcium hydroxide will be applied at several doses. Nitrogen (total Kjeldahl nitrogen (TKN),  $\text{NH}_4$ ,  $\text{NO}_2 + \text{NO}_3$ ), phosphorus (total (TP), total dissolved (TDP) and soluble reactive (SRP) phosphorus), calcium and iron ( $\text{Fe}^{2+}$ ) concentrations in the water in the tanks will be determined every two weeks. Interstitial water samples will be collected from the



sediments every two weeks and analyzed for  $\text{NH}_4$ , TDP, calcium and iron ( $\text{Fe}^{2+}$ ) following the previously-described methods to determine the effect of the treatments on sediment chemistry. Plant growth (increase in shoot length) will be monitored weekly and, at the conclusion of each experiment, plants will be harvested, weighed and the amount of phosphorus, nitrogen and calcium incorporated into the tissue will be determined. All chemical analyses will be done following standard limnological and botanical techniques. The impact of the various lime treatments and their doses on aquatic weed growth and sediment chemistry will then be determined by comparing: (1) plant biomass, growth and tissue nutrient concentrations, and (2) sediment nitrogen and phosphorus concentrations with the type and concentration of lime treatment.

Fish will be sampled at the discretion of Alberta Fisheries and Wildlife in order to assess possible direct effects of liming on fish community structure and growth. While it is not expected that liming will be hazardous to fishes, reduced algal production may decrease the demand for oxygen by sediments under ice during winter, and consequently enhance both over-winter survival and growth of fish.

## Logistics of Lime Application

Lime will be applied to the study lakes (experimental and long-term) using a barge following techniques used by Prepas and Babin (1990). Briefly, lime is applied to the surface of the lakes as a slurry via a custom made barge. The lime is delivered to the lake either in 25 kg bags or in bulk form with a transport truck. Bagged lime is loaded into the barge by hand; the bulk lime is transferred pneumatically. Barge capacity is approximately six Tonne. Once the lime is loaded, the barge makes transects around the lake and discharges lime as a slurry onto the surface of the lake. The slurry is formed by mixing with lake water and the mixture is spread onto the surface through 12 foot booms. The barge is designed to apply the lime at a rate of 6 Tonne/hour.

## Research Participants

Corporate Partners: Continental Lime Company: CLC will supply lime and may other research costs. They will work with us to find support for lime transportation costs.

Lime Application and Logistics: Hydroqual Consultants, Calgary, Alberta. Mr. J. Babin, based in Edmonton, Alberta

Aquatic Chemistry: Open-water and sediment chemistry Dr. E.E. Prepas and Dr. P.J. Curtis to be based at the University of Alberta in collaboration with AEC.

Phytoplankton: Algal biomass and species composition will be analyzed by Mrs. Zhang Ying, PhD student in the Department of Zoology at the University of Alberta

Macrophytes: to be followed by Dr. Patricia Chambers, (Department of Zoology, University of Alberta and NHRI, Saskatoon) for the study lakes and complimented by laboratory experiments at Meanook Biological Research Station and at NHRI, Saskatoon.

Fish: To be sample in collaboration with Jim Moore (AEC), Maurice Drouin and Dave Walty (Alberta Forestry Lands and Wildlife).

Long-term Ecosystem Effects: P.J. Curtis, E.E. Prepas, and D.W. Schindler, Department of Zoology, University of Alberta.

#### Anticipated Results.

It is anticipated that 1) liming will increase the capacity of treated lakes sediments to bind phosphorus, 2) algal concentration and biomass will decrease with decreasing phosphorus concentration in water, 3) Largest improvements in water quality will occur in lakes with lowest pre-treatment phosphorus-binding capacity in sediments. 4) the algal community may shift from undesirable blue-green algae to desirable green algae, 5) abundances of aquatic macrophytes will be unaffected by changes in water transparency and may decline with decreasing concentrations of available phosphorus in sediments, 6) over-winter fish survival may increase when algal production and consequently sediment oxygen demand declines.

### Significance of the Proposed Study.

The proposed experiments will demonstrate the effectiveness of lime treatment in improving water quality and will quantify the links among lime treatment, enhanced phosphorus-binding in sediments and decreased algal concentration and biomass. In addition we will develop simple mathematical models to predict the cost effectiveness of liming and the frequency of lime treatment sufficient to attain specified levels of water quality, based on measured or estimated concentrations of phosphorus and phosphorus-binding materials in sediment, and measured or estimated burial rate of added lime. The proposed research and anticipated contributions represent a huge leap in the understanding of basic biological and geochemical processes in freshwater lakes in the Canadian prairie provinces and hold great potential for increasing the amount of high quality lakes for recreation in a region where lake quality is often perceived as poor by the end user.



## Preliminary Timetable.

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### Winter 1990.

Survey potential experimental and reference lakes.  
Continue monitoring Halfmoon Lake and Figure Eight Lake.

### Open water 1990

Begin collection of background data on experimental and reference lakes.  
Continue monitoring Halfmoon Lake and Figure Eight Lake.  
Treat Figure Eight Lake with lime (.625 tonnes/ha each of calcium hydroxide and calcium carbonate).

### Winter 1990-1

Continue monitoring experimental, reference and long-term experimental lakes.  
Workshop on Lake Management and Restoration.

### Open water 1991

Continue monitoring of experimental, reference and long-term lakes.  
Treat three study lakes if feasible (either both experimental lakes or one experimental lake and long-term Halfmoon Lake) lime, otherwise delay liming one of the lakes for one year.  
(estimated dosage 140 g calcium/m<sup>2</sup>)

### Winter 1991-2

Continue monitoring experimental, reference and long-term experimental lakes.  
Agency Progress Reports

### Open water 1992

Monitoring of experimental, reference and long-term lakes.  
Treat Figure Eight Lake with lime (dosage same as 1990).  
Complete liming scheduled for 1991.

### Winter 1992-3

Monitoring experimental, reference and long-term lakes.  
Agency Progress Reports  
Workshop on Lake Liming.

### Open water 1993

Monitoring of experimental, reference and long-term lakes.  
Treat Halfmoon Lake and Experimental Lakes with lime (3.5 tonnes/ha calcium hydroxide)

### Winter 1993-4

Monitoring of experimental, reference and long-term lakes.  
Agency Progress Reports.

### Open Water 1994

Monitoring of experimental, reference and long-term lakes.

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## APPENDIX B

### LABORATORY ANALYSES CONDUCTED AT THE UNIVERSITY OF ALBERTA

#### OPEN WATER

##### **MAJOR IONS (Ca, Mg, Na, K)**

Water samples were acidified with 1 ml of 10% concentrated  $\text{HNO}_3$  and stored in 250-ml polystyrene bottles. The samples were analyzed on absorption or emission mode on a Perkin-Elmer 3030 Atomic Absorption Spectrophotometer (Perkin-Elmer 1982). Ion concentrations were determined from the mean of 15 readings taken at 3 second intervals.

##### **TEMPERATURE**

Temperature was measured at 1-m intervals from the surface with a Montedoro-Whitney resistance thermometer, accurate to  $0.1^\circ\text{C}$ .

##### **LIGHT**

Light levels were measured with a Protomatic photometer. Light penetration (water transparency) was measured with a Secchi disk.

##### **DISSOLVED OXYGEN**

Duplicate water samples were collected in glass bottles and fixed in the field. This preservation and subsequent analysis followed Carpenter's (1965) modified Winkler technique.

##### **PHOSPHORUS**

Water samples were refrigerated in 1-L Nalgene bottles. For total phosphorus determination, 50-ml duplicate subsamples were poured directly into culture tubes with approximately 0.4 g of potassium persulphate. Total dissolved phosphorus samples were filtered under low pressure ( $\sim 50$  kPa) through a 0.45- $\mu\text{m}$  Millipore Hawp membrane filter prior to being poured into the culture tubes. Menzel and Corwin's (1965) potassium persulphate method was used to determine phosphorus concentrations.

##### **pH**

pH was measured with a Fisher Accumet Model 520 Digital pH/ion meter.

##### **ALKALINITY**

The potentiometric titration method (Environment Canada 1979) was used to determine total alkalinity.

##### **CONDUCTIVITY**

Samples were brought to  $25^\circ\text{C}$  and conductivity measured on a Metrohm conductivity meter (model E587).

**CHLOROPHYLL a**

Samples were collected in opaque Nalgene bottles. Within 6 hours of collection, triplicate samples were prepared for Chla determination. For each sample, a known volume of water was filtered under low pressure (~50 kPa) through a Whatman GF/C filter with 2 ml of a suspension of magnesium carbonate. Filters were frozen in a petri dish for later analysis. Subsequent analysis used a spectrophotometric technique based on the ethanol extraction procedure of M. Ostrofsky, described by Bergmann and Peters (1980).

**SULFATE**

Samples were analyzed with a Dionex ion chromatogram model 2000i/sp.

**COLOR**

Samples were centrifuged for 10 minutes and color was determined on a Hazen platinum-cobalt scale with a Helige aqua, model 611A colorometer.

**TURBIDITY**

Turbidity was measured with a Hach turbidimeter, model 2100A.

**NH<sub>4</sub>, NO<sub>2</sub> AND NO<sub>3</sub>**

All three parameters were analyzed on a Technicon AutoAnalyzer. NO<sub>2</sub> and NO<sub>3</sub> were analyzed by the cadmium-copper reduction method of Stainton et al. (1977). NH<sub>3</sub> was analyzed by the phenol-hypochlorite reaction after Solorzano (1969) as described in Stainton et al. (1977)

**SEDIMENT ANALYSIS CONDUCTED AT THE UNIVERSITY OF ALBERTA**

Core samples were weighed and dried in an oven (65°C) for 48 to 72 hours. The sediments were reweighed then ground with a mortar and pestle. Approximately 1.0 g subsamples were extracted with 10 ml of concentrated (1:1) HCl for 16 hours. This mixture was warmed in a water bath at 90°C for 90 minutes prior to being filtered through a Whatman #44 filter. Concentrated extract was used for copper and sodium analysis using atomic absorption spectroscopy. Subsamples were diluted for metal and phosphorus analysis, the former using atomic absorption and the latter, the persulfate digestion technique after Menzel and Corwin (1965).

APPENDIX C

## ANALYTICAL RESULTS OF WATER AND SEDIMENT SAMPLES



Table C-1. Temperature (C) in Halfmoon Lake, 1989

|       | May 9  | May 16  | May 25  | May 30 | June 6 | June 12 | June 21 | June 28 |         |        |        |  |
|-------|--------|---------|---------|--------|--------|---------|---------|---------|---------|--------|--------|--|
| Depth |        |         |         |        |        |         |         |         |         |        |        |  |
| 0.0 m | 11.1   | 14.6    | ---     | 17.8   | 17.0   | 21.8    | 18.8    | 17.1    |         |        |        |  |
| 0.2 m | 11.1   | 14.6    | ---     | 15.7   | 19.0   | 20.2    | 18.8    | 17.1    |         |        |        |  |
| 0.5 m | 11.0   | 14.6    | ---     | 15.5   | 19.0   | 20.2    | 18.8    | 17.1    |         |        |        |  |
| 1.0 m | 10.9   | 14.6    | ---     | 15.3   | 19.0   | 20.2    | 18.7    | 17.1    |         |        |        |  |
| 2.0 m | 10.3   | 13.5    | ---     | 14.1   | 17.5   | 20.1    | 18.4    | 17.0    |         |        |        |  |
| 3.0 m | 9.3    | 12.5    | ---     | 12.9   | 16.5   | 19.8    | 18.4    | 16.9    |         |        |        |  |
| 4.0 m | 8.5    | 11.5    | ---     | 12.3   | 14.5   | 18.1    | 18.2    | 16.8    |         |        |        |  |
| 5.0 m | 8.2    | 10.8    | ---     | 11.7   | 12.5   | 14.4    | 16.0    | 16.7    |         |        |        |  |
| 6.0 m | 7.9    | 10.4    | ---     | 11.2   | 11.6   | 12.5    | 12.5    | 13.3    |         |        |        |  |
| 7.0 m | 7.6    | 10.0    | ---     | 11.0   | 11.2   | 11.7    | 11.6    | 11.3    |         |        |        |  |
| 7.5 m | 7.3    | ---     | ---     | 11.0   | 11.1   | 11.5    | 11.4    | 10.9    |         |        |        |  |
| 8.0 m | 7.2    | ---     | ---     | 10.8   | ---    | 11.4    | 11.2    | 10.7    |         |        |        |  |
|       |        |         |         |        |        |         |         |         |         |        |        |  |
|       | July 5 | July 19 | July 25 | Aug 2  | Aug 8  | Aug 23  | Aug 28  | Sept 5  | Sept 19 | Oct 17 | Oct 26 |  |
| Depth |        |         |         |        |        |         |         |         |         |        |        |  |
| 0.0 m | 22.5   | 20.6    | 20.1    | 19.1   | 21.0   | 19.3    | 17.1    | 15.7    | 13.0    | 7.6    | 6.5    |  |
| 0.2 m | 19.3   | 20.8    | 20.2    | 20.0   | ---    | 19.5    | 17.1    | 15.7    | 13.0    | 7.6    | 6.5    |  |
| 0.5 m | 19.4   | 20.8    | 20.1    | 20.2   | ---    | 19.5    | 17.1    | 15.7    | 13.0    | 7.6    | 6.5    |  |
| 1.0 m | 19.5   | 20.5    | 20.0    | 20.2   | 22.0   | 19.5    | 17.1    | 15.7    | 12.9    | 7.6    | 6.5    |  |
| 2.0 m | 19.4   | 19.5    | 20.0    | 20.4   | 21.5   | 19.3    | 17.2    | 15.7    | 12.9    | 7.6    | 6.5    |  |
| 3.0 m | 19.3   | 19.5    | 20.0    | 20.0   | 21.3   | 19.2    | 17.2    | 15.7    | 12.8    | 7.6    | 6.5    |  |
| 4.0 m | 18.5   | 19.0    | 20.0    | 18.2   | 21.0   | 19.1    | 17.2    | 15.6    | 12.8    | 7.6    | 6.5    |  |
| 5.0 m | 17.6   | 16.5    | 17.0    | 16.5   | ---    | 18.2    | 17.2    | 15.4    | 12.8    | 7.6    | 6.5    |  |
| 6.0 m | 15.0   | 14.6    | 15.0    | 14.7   | ---    | 15.4    | 15.8    | 15.2    | 12.7    | 7.6    | 6.5    |  |
| 7.0 m | 12.6   | 13.0    | 13.7    | 13.8   | ---    | 13.7    | 13.5    | 14.6    | 12.6    | 7.6    | 6.5    |  |
| 7.5 m | 11.9   | 12.6    | 13.0    | 13.1   | ---    | 13.0    | 12.7    | 14.0    | 12.6    | 7.6    | 6.5    |  |
| 8.0 m | 11.7   | ---     | 12.8    | 12.5   | ---    | 12.7    | 12.5    | 13.0    | 12.5    | 7.6    | 6.5    |  |

Table C-2. Dissolved Oxygen (mg/L) in Halfmoon Lake, 1989

|       | May 9  | May 16  | May 25  | May 30 | June 5 | June 13 | June 21 | June 28 |        |        |  |
|-------|--------|---------|---------|--------|--------|---------|---------|---------|--------|--------|--|
| Depth |        |         |         |        |        |         |         |         |        |        |  |
| 1.0 m | 14.0   | 12.3    | 11.3    | 14.6   | 13.2   | 11.3    | 9.77    | 9.64    |        |        |  |
| 2.0 m | 12.9   | 12.6    | 11.1    | 14.3   | 12.5   | 11.4    | 9.60    | 9.42    |        |        |  |
| 3.0 m | 12.7   | 11.9    | 10.9    | 14.2   | 10.8   | 10.5    | ---     | 9.22    |        |        |  |
| 4.0 m | 9.99   | 8.69    | 10.8    | 13.0   | 8.32   | 11.2    | 9.14    | 9.01    |        |        |  |
| 5.0 m | 8.39   | 6.52    | 10.9    | 9.84   | 5.40   | 11.3    | ---     | 8.12    |        |        |  |
| 6.0 m | 7.28   | 6.88    | 10.4    | 7.98   | 2.55   | 0.70    | 0.01    | 0.37    |        |        |  |
| 7.0 m | 7.25   | 2.21    | 10.4    | 5.33   | 0.33   | 0.22    | ---     | 0.15    |        |        |  |
| 7.5 m | 4.75   | 1.32    | ---     | 3.07   | ---    | 0.14    | 0.00    | 0.10    |        |        |  |
|       |        |         |         |        |        |         |         |         |        |        |  |
|       | July 5 | July 19 | July 25 | Aug 2  | Aug 8  | Aug 23  | Aug 28  | Sept 19 | Oct 17 | Oct 26 |  |
| Depth |        |         |         |        |        |         |         |         |        |        |  |
| 1.0 m | 12.0   | 17.0    | 11.4    | 9.37   | 3.65   | 9.75    | 4.99    | 7.10    | 8.99   | 9.37   |  |
| 2.0 m | 11.6   | 12.1    | 11.0    | 9.27   | 2.83   | 9.57    | 4.95    | 7.17    | 9.09   | 9.48   |  |
| 3.0 m | 10.8   | 9.22    | 11.3    | 7.58   | 0.99   | 7.36    | 4.91    | 7.07    | 9.08   | 9.35   |  |
| 4.0 m | 7.83   | 5.23    | 11.5    | 1.22   | 0.12   | 6.79    | 4.90    | ---     | 9.23   | 9.33   |  |
| 5.0 m | 5.68   | 0.86    | 8.30    | 0.00   | 0.00   | 0.41    | 4.49    | 6.46    | 9.23   | 9.37   |  |
| 6.0 m | 0.19   | 0.00    | 0.29    | 0.00   | 0.00   | 0.00    | 0.00    | 7.00    | 9.02   | 9.35   |  |
| 7.0 m | 0.00   | 0.00    | 0.00    | 0.00   | 0.00   | 0.00    | 0.00    | 5.12    | 9.27   | 9.33   |  |
| 7.5 m | 0.00   | 0.00    | 0.00    | 0.00   | 0.00   | 0.00    | 0.00    | 4.81    | 9.96   | 9.31   |  |

Table C-3. Light Levels (foot-candles) in Halfmoon Lake, 1989

|       | May 9 | May 16 | May 25 | May 30 | June 6 | June 13 | June 21 | June 28 |  |  |  |  |
|-------|-------|--------|--------|--------|--------|---------|---------|---------|--|--|--|--|
| Depth |       |        |        |        |        |         |         |         |  |  |  |  |
| 0.0 m | 6000  | 2500   | ---    | 5000   | 1000   | 4600    | 3500    | 4000    |  |  |  |  |
| 0.2 m | 2700  | 1800   | ---    | 3000   | 350    | 2200    | 2800    | 3500    |  |  |  |  |
| 0.5 m | 1400  | 1500   | ---    | 1500   | 150    | 1400    | 1900    | 2000    |  |  |  |  |
| 1.0 m | 1000  | 1000   | ---    | 1200   | 100    | 1000    | 1300    | 1000    |  |  |  |  |
| 2.0 m | 300   | 350    | ---    | 8500   | 45     | 380     | 520     | 300     |  |  |  |  |
| 3.0 m | 88    | 95     | ---    | 150    | 15     | 160     | 175     | 100     |  |  |  |  |
| 4.0 m | 32    | 60     | ---    | 75     | 9.0    | 58      | 68      | 25      |  |  |  |  |
| 5.0 m | 10    | 30     | ---    | 30     | 3.5    | 27      | 24      | 6.5     |  |  |  |  |
| 6.0 m | 5.2   | 10     | ---    | 10     | 1.0    | 10      | 11      | 2.5     |  |  |  |  |
| 7.0 m | 3.6   | 5.5    | ---    | 5.0    | 0.5    | 5.4     | 4.5     | 1.0     |  |  |  |  |
| 7.5 m | ---   | ---    | ---    | 3.5    | ---    | 3.4     | 2.9     | 0.68    |  |  |  |  |
| 8.0 m | 2.5   | ---    | ---    | ---    | ---    | ---     | 2.4     | 0.53    |  |  |  |  |

|       | July 5 | July 19 | July 25 | Aug 2 | Aug 8 | Aug 23 | Aug 28 | Sept 5 | Sept 19 | Oct 17 | Oct 26 |
|-------|--------|---------|---------|-------|-------|--------|--------|--------|---------|--------|--------|
| Depth |        |         |         |       |       |        |        |        |         |        |        |
| 0.0 m | 4900   | 6000    | 3990    | 6300  | 1000  | 3500   | 1550   |        |         |        |        |
| 0.2 m | 3700   | 1200    | 1500    | 2000  | 500   | 3000   | 770    | 2500   | 3100    | 4100   | 4200   |
| 0.5 m | 2000   | 400     | 510     | 150   | 280   | 1500   | 460    | 1000   | 1100    | 2000   | 1400   |
| 1.0 m | 1100   | 35      | 51      | 60    | 170   | 1000   | 240    | 610    | 560     | 850    | 720    |
| 2.0 m | 180    | 0.0     | 0.0     | 7.0   | 100   | 300    | 91     | 370    | 410     | 550    | 260    |
| 3.0 m | 30     | 0.0     | 0.0     | 0.0   | 37    | 90     | 37     | 150    | 140     | 170    | 100    |
| 4.0 m | 4.5    | 0.0     | 0.0     | 0.0   | 20.0  | 2.0    | 16     | 47     | 62      | 75     | 49     |
| 5.0 m | 0.0    | 0.0     | 0.0     | 0.0   | 10.0  | 0.0    | 6.8    | 12     | 26      | 40     | 27     |
| 6.0 m | 0.0    | 0.0     | 0.0     | 0.0   | 4.0   | 0.0    | 1.2    | 4.5    | 8.3     | 13     | 13     |
| 7.0 m | 0.0    | 0.0     | 0.0     | 0.0   | 1.5   | 0.0    | 0.0    | ---    | 3.4     | 5.1    | 4.9    |
| 7.5 m | 0.0    | 0.0     | 0.0     | 0.0   | 0.0   | 0.0    | 0.0    | ---    | 1.3     | 2.0    | 2.3    |
| 8.0 m | 0.0    | 0.0     | 0.0     | 0.0   | 0.0   | 0.0    | 0.0    | ---    | 0.9     | ---    | 1.6    |

Table C-4. pH and Alkalinity in Halfmoon Lake, 1989

|   | May 9 | May 16 | May 25 | May 30 | June 6 | June 13 | June 21 | June 28 |
|---|-------|--------|--------|--------|--------|---------|---------|---------|
| pH  |       |        |        |        |        |         |         |         |
| 0.0 m   | 8.26  | 8.38   | 8.14   | 8.22   | 8.59   | 8.59    | 8.50    | 8.75    |
| 1.0 m   | 8.24  | 8.35   | 8.26   | 8.32   | 8.66   | 8.65    | ---     | 8.71    |
| 2.0 m   | 8.28  | 8.26   | 8.23   | 8.52   | 8.62   | 8.60    | 8.48    | 8.76    |
| 4.0 m   | 8.00  | 7.93   | 8.27   | 8.37   | 8.06   | 8.63    | 8.28    | 8.83    |
| 6.0 m   | 7.80  | 7.90   | 8.26   | 8.06   | 7.95   | 8.35    | 7.80    | 7.75    |
| 7.5 m   | 7.71  | 7.82   | 8.12   | 7.79   | ---    | 7.76    | 7.40    | 7.64    |
| 0-2.5 m   | 8.22  | 8.22   | 7.78   | 8.36   | 8.61   | 8.56    | 8.20    | 8.57    |
| Tot. Alkalinity<br>(mg/L as CaCO <sub>3</sub> ) |       |        |        |        |        |         |         |         |
| 0.0 m   | 219   | 217    | 238    | 222    | 160    | 164     | 159     | 128     |
| 1.0 m   | 221   | 214    | 235    | 204    | 162    | 158     | ---     | 148     |
| 2.0 m   | 208   | 203    | 209    | 199    | 164    | 153     | 154     | 162     |
| 4.0 m   | 202   | 184    | 196    | 220    | 165    | 153     | 152     | 165     |
| 6.0 m   | 199   | 194    | 204    | 207    | 170    | 157     | 175     | 188     |
| 7.5 m   | 207   | 181    | 206    | 222    | ---    | 177     | 181     | 196     |
| 0-2.5 m   | 179   | 203    | 198    | 205    | 162    | 156     | 156     | ---     |
| Carbonate (mg/L)                                |       |        |        |        |        |         |         |         |
| 0.0 m   | 0.00  | 0.00   | 0.00   | 0.00   | 4.44   | 6.71    | 3.96    | 6.35    |
| 1.0 m   | 0.00  | 0.00   | 0.00   | 0.00   | 4.56   | 5.16    | ---     | 8.51    |
| 2.0 m   | 0.00  | 0.00   | 0.00   | 0.00   | 4.80   | 5.16    | 4.56    | 8.03    |
| 4.0 m   | 0.00  | 0.00   | 0.00   | 0.00   | 0.00   | 5.16    | 0.00    | 7.43    |
| 6.0 m   | 0.00  | 0.00   | 0.00   | 0.00   | 0.00   | 0.00    | 0.00    | 0.00    |
| 7.5 m   | 0.00  | 0.00   | 0.00   | 0.00   | ---    | 0.00    | 0.00    | 0.00    |
| 0-2.5 m   | 0.00  | 0.00   | 0.00   | 0.00   | 3.00   | 4.32    | 0.00    | ---     |
| Bicarbonate<br>(mg/L)                           |       |        |        |        |        |         |         |         |
| 0.0 m   | 268   | 264    | 290    | 271    | 186    | 186     | 186     | 143     |
| 1.0 m   | 269   | 261    | 287    | 249    | 188    | 182     | ---     | 163     |
| 2.0 m   | 253   | 248    | 254    | 233    | 190    | 176     | 179     | 181     |
| 4.0 m   | 246   | 224    | 240    | 268    | 202    | 176     | 186     | 187     |
| 6.0 m   | 243   | 237    | 249    | 252    | 208    | 192     | 213     | 229     |
| 7.5 m   | 252   | 221    | 251    | 271    | ---    | 216     | 221     | 239     |
| 0-2.5 m   | 218   | 248    | 241    | 250    | 191    | 182     | 190     | ---     |



Table C-4 (cont'd)

|   | July 5 | July 19 | July 25 | Aug 2 | Aug 9 | Aug 10 | Aug 15 | Aug 18 | Aug 28 | Sept 19 | Oct 17 | Oct 26 |
|---|--------|---------|---------|-------|-------|--------|--------|--------|--------|---------|--------|--------|
| pH  |        |         |         |       |       |        |        |        |        |         |        |        |
| 0.0 m   | 8.87   | 9.13    | 9.17    | 9.14  | 8.10  | ---    | ---    | ---    | 9.75   | 8.60    | 8.86   | 8.33   |
| 1.0 m   | 8.79   | 9.07    | 9.12    | 9.13  | 8.10  | ---    | ---    | ---    | 9.74   | 8.83    | 8.88   | 8.52   |
| 2.0 m   | 8.72   | 8.91    | 9.01    | 9.10  | 8.08  | ---    | ---    | ---    | 9.73   | 8.77    | 8.90   | 8.30   |
| 4.0 m   | 8.58   | 8.44    | 9.09    | 8.40  | 8.07  | ---    | ---    | ---    | 9.73   | 8.51    | 8.95   | 8.20   |
| 6.0 m   | 7.95   | 7.85    | 8.10    | 7.92  | 7.95  | ---    | ---    | ---    | 8.24   | 8.58    | 8.89   | 8.50   |
| 7.5 m   | 7.61   | 7.81    | 7.81    | 7.76  | 7.75  | ---    | ---    | ---    | 8.29   | 8.53    | 8.89   | 8.33   |
| 0-2.5 m   | 8.83   | 9.10    | 9.19    | 9.09  | 8.16  | #9.36  | #9.83  | #10.0  | 9.66   | 8.62    | 8.84   | 8.33   |
| Tot. Alkalinity<br>(mg/L as CaCO <sub>3</sub> ) |        |         |         |       |       |        |        |        |        |         |        |        |
| 0.0 m   | 173    | 152     | 145     | 128   | 132   | ---    | ---    | ---    | 116    | 131     | 127    | 126    |
| 1.0 m   | 173    | 152     | 142     | 126   | 136   | ---    | ---    | ---    | 118    | 131     | 125    | 125    |
| 2.0 m   | 176    | 153     | 137     | 124   | 132   | ---    | ---    | ---    | 115    | 130     | 126    | 127    |
| 4.0 m   | 173    | 162     | 119     | 134   | 133   | ---    | ---    | ---    | 118    | 135     | 126    | 125    |
| 6.0 m   | 181    | 200     | 159     | 174   | 154   | ---    | ---    | ---    | 183    | 142     | 126    | 124    |
| 7.5 m   | 203    | 214     | 188     | 198   | 196   | ---    | ---    | ---    | 225    | 133     | 123    | 125    |
| 0-2.5 m   | 176    | 146     | 137     | 128   | 132   | #129   | #127   | #127   | 114    | 134     | 126    | 125    |
| Carbonate (mg/L)                                |        |         |         |       |       |        |        |        |        |         |        |        |
| 0.0 m   | 11.8   | 11.9    | 15.5    | 13.4  | 0.00  | ---    | ---    | ---    | 33.6   | 12.5    | 11.4   | 0.00   |
| 1.0 m   | 14.3   | 11.8    | 9.11    | 12.2  | 0.00  | ---    | ---    | ---    | 33.5   | 19.3    | 9.59   | 3.36   |
| 2.0 m   | 8.63   | 7.79    | 8.63    | 11.4  | 0.00  | ---    | ---    | ---    | 32.7   | 11.0    | 12.0   | 0.00   |
| 4.0 m   | 8.39   | 0.84    | 11.3    | 1.20  | 0.00  | ---    | ---    | ---    | 33.8   | 6.59    | 12.5   | 0.00   |
| 6.0 m   | 0.00   | 0.00    | 0.00    | 0.00  | 0.00  | ---    | ---    | ---    | 0.00   | 10.3    | 12.7   | 3.83   |
| 7.5 m   | 0.00   | 0.00    | 0.00    | 0.00  | 0.00  | ---    | ---    | ---    | 0.00   | 7.31    | 9.59   | 0.00   |
| 0-2.5 m   | #17.2  | 12.6    | 14.8    | 13.7  | 0.00  | #23.7  | #38.9  | #45.3  | 30.3   | 10.1    | 12.3   | 0.00   |
| Bicarbonate<br>(mg/L)                           |        |         |         |       |       |        |        |        |        |         |        |        |
| 0.0 m   | 187    | 161     | 146     | 128   | 161   | ---    | ---    | ---    | ---    | 134     | 131    | 154    |
| 1.0 m   | 181    | 162     | 155     | 128   | 165   | ---    | ---    | ---    | ---    | 120     | 133    | 149    |
| 2.0 m   | 197    | 171     | 150     | 128   | 161   | ---    | ---    | ---    | ---    | 136     | 123    | 155    |
| 4.0 m   | 194    | 196     | 123     | 162   | 162   | ---    | ---    | ---    | ---    | 151     | 128    | 152    |
| 6.0 m   | 220    | 244     | 194     | 212   | 188   | ---    | ---    | ---    | ---    | 152     | 127    | 147    |
| 7.5 m   | 248    | 260     | 229     | 241   | 240   | ---    | ---    | ---    | ---    | 147     | 131    | 152    |
| 0-2.5 m   | 179    | 152     | 137     | 128   | 161   | #109   | #75.2  | #52.8  | ---    | 142     | 129    | 152    |

Table C-5. Conductivity (uS/cm) in Halfmoon Lake, 1999.

|         | May 9 | May 16 | May 25 | May 30 | June 6 | June 13 | June 21 | June 28 |
|---------|-------|--------|--------|--------|--------|---------|---------|---------|
| Depth   |       |        |        |        |        |         |         |         |
| 0.0 m   | 370   | 359    | ---    | 385    | 405    | 360     | 335     | 398     |
| 1.0 m   | 370   | 361    | ---    | 385    | 410    | 360     | 369     | 395     |
| 2.0 m   | 380   | 352    | ---    | 385    | 410    | 360     | 328     | 405     |
| 4.0 m   | 380   | 370    | ---    | 375    | 410    | 360     | 340     | 402     |
| 6.0 m   | 390   | 350    | ---    | 370    | 425    | 360     | 380     | 405     |
| 7.5 m   | 395   | 380    | ---    | 400    | ---    | 400     | 393     | 410     |
| 0-2.5 m | 370   | 369    | ---    | 375    | 400    | 360     | 349     | 360     |

|         | July 5 | July 19 | July 25 | Aug 2 | Aug 8 | Aug 15 | Aug 18 | Aug 23 | Sept 19 | Oct 17 | Oct 26 |
|---------|--------|---------|---------|-------|-------|--------|--------|--------|---------|--------|--------|
| Depth   |        |         |         |       |       |        |        |        |         |        |        |
| 0.0 m   | 390    | 310     | 348     | 340   | 325   | 335    | 398    | 320    | 310     | 295    | 340    |
| 1.0 m   | 380    | 325     | 348     | 340   | 320   | 369    | 395    | 310    | 305     | 310    | 340    |
| 2.0 m   | 400    | 320     | 345     | 310   | 322   | 328    | 405    | 321    | 302     | 325    | 335    |
| 4.0 m   | 400    | 350     | 352     | 330   | 322   | 340    | 402    | 321    | 295     | 315    | 335    |
| 6.0 m   | 410    | 410     | 420     | 390   | 360   | 380    | 405    | 460    | 310     | 325    | 335    |
| 7.5 m   | 470    | 440     | 485     | 415   | 431   | 393    | 410    | 540    | 302     | 335    | 335    |
| 0-2.5 m | 400    | 315     | 345     | ---   | 320   | 349    | ---    | 310    | 300     | 335    | 340    |

Table C-6. Color (ag/L as Pt) and Turbidity (NTU) in Halfmoon Lake, 1989.

| Color     | May 9  | May 16  | May 25  | May 30 | June 6 | June 13 | June 21 | June 28 |        |        |  |
|-----------|--------|---------|---------|--------|--------|---------|---------|---------|--------|--------|--|
| Depth     |        |         |         |        |        |         |         |         |        |        |  |
| 0.0 m     | 12.5   | 12.5    | 12.5    | 20.0   | 20.0   | 17.5    | 20.0    | 17.5    |        |        |  |
| 1.0 m     | 12.5   | 12.5    | 12.5    | 20.0   | 20.0   | 17.5    | 18.8    | 20.0    |        |        |  |
| 2.0 m     | 12.5   | 12.5    | 13.8    | 20.0   | 20.0   | 17.5    | 17.5    | 15.0    |        |        |  |
| 4.0 m     | 12.5   | 15.0    | 13.8    | 20.0   | 18.8   | 17.5    | 17.5    | 20.0    |        |        |  |
| 6.0 m     | 12.5   | 15.0    | 13.8    | 20.0   | 20.0   | 20.0    | 20.0    | 17.5    |        |        |  |
| 7.5 m     | 12.5   | 17.5    | 15.0    | 18.8   | ---    | 20.0    | 20.0    | 20.0    |        |        |  |
| 0-2.5 m   | 12.5   | 13.8    | 12.5    | 20.0   | 20.0   | 18.8    | 25.0    | 12.5    |        |        |  |
|           | July 5 | July 19 | July 25 | Aug 2  | Aug 8  | Aug 23  | Aug 28  | Sept 19 | Oct 17 | Oct 26 |  |
| Depth     |        |         |         |        |        |         |         |         |        |        |  |
| 0.0 m     | 12.5   | 15.0    | 18.8    | 25.0   | 17.5   | 20.0    | 17.5    | 17.0    | 10.0   | 7.5    |  |
| 1.0 m     | 17.5   | 13.8    | 12.5    | 25.0   | 15.0   | 20.0    | 18.8    | 10.0    | 10.0   | 7.5    |  |
| 2.0 m     | 13.8   | 17.5    | 15.0    | 20.0   | 17.5   | 20.0    | 20.0    | 10.0    | 10.0   | 10.0   |  |
| 4.0 m     | 12.5   | 17.5    | 20.0    | 16.3   | 17.5   | 22.5    | 20.0    | 10.0    | 10.0   | 10.0   |  |
| 6.0 m     | 10.0   | 20.0    | 16.3    | 20.0   | 18.8   | 22.5    | 20.0    | 10.0    | 12.0   | 12.5   |  |
| 7.5 m     | 12.5   | 25.0    | 25.0    | 25.0   | 25.0   | 25.0    | 22.5    | 10.0    | ---    | 7.5    |  |
| 0-2.5 m   | 12.5   | 20.0    | 18.8    | 22.5   | 15.0   | 20.0    | 18.8    | ---     |        |        |  |
|           | May 9  | May 16  | May 25  | May 30 | June 6 | June 13 | June 21 | June 28 |        |        |  |
| Turbidity |        |         |         |        |        |         |         |         |        |        |  |
| Depth     |        |         |         |        |        |         |         |         |        |        |  |
| 0.0 m     | 3.50   | 2.83    | 2.60    | 3.40   | 6.10   | 5.50    | 3.75    | 5.40    |        |        |  |
| 1.0 m     | 3.55   | 2.88    | 2.88    | 3.50   | 6.25   | 5.40    | 3.58    | 4.90    |        |        |  |
| 2.0 m     | 3.45   | 2.90    | 3.00    | 3.43   | 4.50   | 5.33    | 3.48    | 5.50    |        |        |  |
| 4.0 m     | 3.55   | 2.88    | 3.00    | 3.40   | 3.40   | 5.00    | 3.35    | 5.05    |        |        |  |
| 6.0 m     | 3.40   | 2.90    | 3.00    | 3.30   | 3.45   | 5.00    | 2.48    | 3.25    |        |        |  |
| 7.5 m     | 4.00   | 3.75    | 3.25    | 3.33   | ---    | 4.30    | 3.75    | 4.10    |        |        |  |
| 0-2.5 m   | 3.70   | 2.90    | 3.18    | 3.75   | 6.28   | 6.50    | 3.75    | 5.55    |        |        |  |
|           | July 5 | July 19 | July 25 | Aug 2  | Aug 8  | Aug 23  | Aug 28  | Sept 19 | Oct 17 | Oct 26 |  |
| Depth     |        |         |         |        |        |         |         |         |        |        |  |
| 0.0 m     | 6.10   | 23.5    | 15.0    | 24.0   | 2.38   | 4.48    | 3.50    | 3.0     | 4.5    | 1.6    |  |
| 1.0 m     | 5.85   | 22.3    | 13.5    | 20.5   | 2.38   | 4.90    | 3.92    | 4.2     | 5.6    | 1.8    |  |
| 2.0 m     | 5.50   | 18.8    | 13.8    | 20.0   | 2.33   | 4.70    | 3.92    | 6.2     | 4.4    | 1.7    |  |
| 4.0 m     | 4.08   | 7.45    | 13.5    | 5.00   | 2.28   | 4.55    | 3.42    | 5.2     | 5.1    | 2.3    |  |
| 6.0 m     | 2.38   | 5.63    | 3.95    | 4.10   | 2.58   | 6.40    | 3.25    | 4.5     | 3.8    | 1.8    |  |
| 7.5 m     | 4.45   | 6.33    | 4.60    | 5.40   | 4.65   | 6.25    | 4.10    | 4.9     | 4.6    | 2.0    |  |
| 0-2.5 m   | 6.05   | 23.0    | 14.8    | 22.0   | 2.45   | 4.60    | 4.75    | 3.7     | 5.0    | 1.6    |  |

Table C-7. Total Phosphorus (ug/L) in Halfmoon Lake, 1989.

|         | May 9  | May 16  | May 25  | May 30 | June 6 | June 13 | June 21 | June 28 |        |        |
|---------|--------|---------|---------|--------|--------|---------|---------|---------|--------|--------|
| Depth   |        |         |         |        |        |         |         |         |        |        |
| 0.0 m   | 79.8   | 61.2    | 62.4    | 61.9   | 66.0   | 46.3    | 43.3    | 53.1    |        |        |
| 1.0 m   | 96.3   | 64.0    | 69.0    | 68.3   | 71.3   | 47.7    | 52.0    | 63.1    |        |        |
| 2.0 m   | 96.0   | 68.5    | 68.4    | 68.7   | 61.5   | 44.4    | 45.8    | 59.7    |        |        |
| 4.0 m   | 90.4   | 70.0    | 61.0    | 67.6   | 61.1   | 48.1    | 45.2    | 52.4    |        |        |
| 6.0 m   | 93.0   | 70.4    | 62.5    | 66.1   | 71.9   | 46.5    | 87.3    | 107     |        |        |
| 7.5 m   | 108    | 132     | 66.0    | 78.8   | ---    | 48.3    | 206     | 185     |        |        |
| 0-2.5 m | 85.7   | 58.4    | 64.9    | 66.2   | 68.2   | 53.1    | 53.5    | 59.7    |        |        |
|         |        |         |         |        |        |         |         |         |        |        |
|         | July 5 | July 19 | July 25 | Aug 2  | Aug 8  | Aug 10  | Aug 15  | Aug 18  | Aug 23 | Aug 28 |
| Depth   |        |         |         |        |        |         |         |         |        |        |
| 0.0 m   | 54.2   | 86.4    | 77.6    | 84.4   | 77.6   | ---     | ---     | ---     | 53.3   | 56.1   |
| 1.0 m   | 60.9   | 89.9    | 85.6    | 82.9   | 76.6   | ---     | ---     | ---     | 50.9   | 56.2   |
| 2.0 m   | 64.0   | 87.6    | 79.0    | 83.5   | 71.1   | ---     | ---     | ---     | 52.5   | 60.1   |
| 4.0 m   | 63.4   | 59.7    | 78.6    | 55.7   | 59.2   | ---     | ---     | ---     | 53.5   | 57.1   |
| 6.0 m   | 77.1   | 190     | 80.8    | 219    | 132    | ---     | ---     | ---     | 209    | 243    |
| 7.5 m   | 264    | 326     | 290     | 354    | 359    | ---     | ---     | ---     | 464    | 467    |
| 0-2.5 m | 66.4   | 89.7    | 80.7    | 89.2   | 65.6   | #65.4   | #55.2   | #53.9   | 57.5   | 60.9   |
|         |        |         |         |        |        |         |         |         |        |        |
|         | Sept 5 | Sept 19 | Oct 17  | Oct 26 |        |         |         |         |        |        |
| Depth   |        |         |         |        |        |         |         |         |        |        |
| 0.0 m   | ---    | 88.6    | 72.3    | 67.3   |        |         |         |         |        |        |
| 1.0 m   | ---    | 92.6    | 76.1    | 69.8   |        |         |         |         |        |        |
| 2.0 m   | ---    | 105     | 66.1    | 70.0   |        |         |         |         |        |        |
| 4.0 m   | ---    | 102     | 72.9    | 71.7   |        |         |         |         |        |        |
| 6.0 m   | ---    | 85.2    | 76.4    | 71.0   |        |         |         |         |        |        |
| 7.5 m   | ---    | 87.0    | 71.4    | 64.5   |        |         |         |         |        |        |
| 0-2.5 m | 73.4   | 94.5    | 66.9    | 65.5   |        |         |         |         |        |        |

# composite (0-1m) sample collected during lime treatment



Table C-8. Total Dissolved Phosphorus (ug/L) in Halfmoon Lake, 1989

|         | May 9  | May 16  | May 25  | May 30 | June 6 | June 13 | June 21 | June 28 |        |        |
|---------|--------|---------|---------|--------|--------|---------|---------|---------|--------|--------|
| Depth   |        |         |         |        |        |         |         |         |        |        |
| 0.0 m   | 17.5   | 19.6    | 22.4    | 21.4   | 29.3   | 27.2    | 19.7    | 26.4    |        |        |
| 1.0 m   | 36.0   | 21.6    | 25.6    | 23.2   | 29.2   | 34.2    | 24.3    | 28.6    |        |        |
| 2.0 m   | 33.5   | 20.8    | 27.3    | 27.0   | 23.1   | 31.7    | 22.3    | 26.8    |        |        |
| 4.0 m   | 32.6   | 20.7    | ---     | 23.1   | 22.5   | 25.3    | 23.6    | 26.2    |        |        |
| 6.0 m   | 30.1   | 20.8    | 20.5    | 22.8   | 25.0   | 20.3    | 43.0    | 34.6    |        |        |
| 7.5 m   | 36.4   | 38.8    | 21.3    | 23.5   | ---    | 26.5    | 67.0    | 60.0    |        |        |
| 0-2.5 m | 17.2   | 21.1    | 21.3    | 23.8   | 23.0   | 24.4    | 22.9    | 26.3    |        |        |
|         |        |         |         |        |        |         |         |         |        |        |
|         | July 5 | July 19 | July 25 | Aug 2  | Aug 8  | Aug 10  | Aug 15  | Aug 18  | Aug 23 | Aug 28 |
| Depth   |        |         |         |        |        |         |         |         |        |        |
| 0.0 m   | 20.6   | 24.0    | 24.1    | 20.8   | 26.4   | ---     | ---     | ---     | 20.4   | 21.9   |
| 1.0 m   | 23.0   | 21.4    | 22.5    | 16.5   | 22.2   | ---     | ---     | ---     | 18.9   | 21.0   |
| 2.0 m   | 18.5   | 20.0    | 28.3    | 16.9   | 22.6   | ---     | ---     | ---     | 19.9   | 22.3   |
| 4.0 m   | 18.2   | 16.8    | 21.0    | 15.2   | 15.4   | ---     | ---     | ---     | 21.2   | 19.6   |
| 6.0 m   | 19.6   | 90.8    | 48.5    | 116    | 56.5   | ---     | ---     | ---     | 160    | 194    |
| 7.5 m   | 76.8   | 119     | 134     | 165    | 121    | ---     | ---     | ---     | 265    | 332    |
| 0-2.5 m | 19.3   | 20.3    | 26.1    | 18.4   | 19.6   | #22.1   | #21.4   | #21.3   | 25.4   | 19.7   |
|         |        |         |         |        |        |         |         |         |        |        |
|         | Sept 5 | Sept 19 | Oct 17  | Oct 26 |        |         |         |         |        |        |
| Depth   |        |         |         |        |        |         |         |         |        |        |
| 0.0 m   | ---    | 49.5    | 30.0    | 29.0   |        |         |         |         |        |        |
| 1.0 m   | ---    | 51.1    | 28.1    | 28.6   |        |         |         |         |        |        |
| 2.0 m   | ---    | 61.7    | 22.5    | 28.6   |        |         |         |         |        |        |
| 4.0 m   | ---    | 53.2    | 28.3    | 29.4   |        |         |         |         |        |        |
| 6.0 m   | ---    | 52.1    | 28.9    | 25.2   |        |         |         |         |        |        |
| 7.5 m   | ---    | 59.1    | 25.6    | 26.6   |        |         |         |         |        |        |
| 0-2.5 m | 48.5   | 49.2    | 25.2    | 25.5   |        |         |         |         |        |        |

# composite (0-1m) sample collected during lime treatment

**DISSOLVED**

Table C-9. Total Phosphorus (ug/L), Chlorophyll a (ug/L), and Secchi disk depth (m) from the composite samples

|         | <del>TDP</del> <b>TP</b> | Chl a | Secchi |
|---------|--------------------------|-------|--------|
| 9 May   | 17.2                     | 27.1  | 1.0    |
| 18 May  | 21.1                     | 12.6  | 1.8    |
| 25 May  | 21.3                     | 16.7  | 1.1    |
| 30 May  | 23.8                     | 16.2  | 1.3    |
| 6 June  | 23                       | 17.6  | 0.8    |
| 13 June | 24.4                     | 11.0  | 0.9    |
| 21 June | 22.9                     | 14.7  | 1.1    |
| 28 June | 26.3                     | 16.9  | 1.0    |
| 5 July  | 19.3                     | 23.7  | 0.9    |
| 19 July | 20.3                     | 82.5  | 0.3    |
| 25 July | 26.1                     | 63.2  | 0.3    |
| 2 Aug   | 18.4                     | 64.3  | 0.8    |
| 8 Aug   | 19.6                     | 11.7  | 1.6    |
| 10 Aug* | 22.1                     | ----  | ----   |
| 15 Aug* | 21.4                     | 12.6  | ----   |
| 18 Aug* | 21.3                     | 17.0  | 0.5    |
| 23 Aug  | 25.4                     | 16.7  | 1.0    |
| 28 Aug  | 19.7                     | 11.0  | 1.5    |
| 5 Sept  | 48.5                     | 5.99  | 2.0    |
| 19 Sept | 49.2                     | 15.5  | 2.3    |
| 17 Oct  | 25.2                     | 16.7  | 2.0    |
| 26 Oct  | 25.5                     | 13.6  | 2.1    |

\* (0-1 m) samples collected during lime treatment

Table C-10. Ammonium (ug/L) and Nitrite + Nitrate (ug/L) in Halfmoon Lake, 1989.

## Ammonium

|         | May 9  | May 16  | May 25  | May 30 | June 6 | June 13 | June 21 | June 28 |        |
|---------|--------|---------|---------|--------|--------|---------|---------|---------|--------|
| Depth   |        |         |         |        |        |         |         |         |        |
| 0.0 m   | 8.60   | 6.60    | 4.57    | 4.83   | 3.77   | 6.47    | 0.233   | 7.27    |        |
| 1.0 m   | 8.70   | 9.50    | 4.57    | 5.67   | 3.70   | 6.90    | 0.967   | 7.57    |        |
| 2.0 m   | 9.40   | 21.1    | 5.60    | 6.50   | 3.47   | 7.63    | 1.40    | 87.9    |        |
| 4.0 m   | 49.2   | 22.7    | 6.33    | 12.3   | 3.93   | 7.07    | 2.50    | ---     |        |
| 6.0 m   | 50.9   | 77.0    | 5.87    | 14.0   | 7.47   | 7.63    | 159     | 343     |        |
| 7.5 m   | 50.4   | 83.2    | 6.20    | 17.4   | ---    | 368     | 601     | 719     |        |
| 0-2.5 m | 14.4   | 10.6    | 6.00    | ---    | 3.63   | 9.13    | ---     | 10.5    |        |
|         | July 5 | July 19 | July 25 | Aug 2  | Aug 8  | Aug 23  | Aug 28  | Sept 19 | Oct 17 |
| Depth   |        |         |         |        |        |         |         |         |        |
| 0.0 m   | 7.50   | 23.7    | 18.9    | 105    | 519    | 228     | 279     | 641     | 184    |
| 1.0 m   | 5.55   | 18.9    | 16.8    | 72.8   | 528    | 102     | 196     | 675     | 183    |
| 2.0 m   | 5.10   | 21.8    | 15.0    | 109    | 582    | 87.0    | 184     | 662     | 151    |
| 4.0 m   | 12.8   | 72.3    | 11.2    | 203    | 573    | 170     | 202     | 668     | 191    |
| 6.0 m   | 63.4   | 1116    | 269     | 2960   | 1104   | 1784    | 2498    | 634     | 149    |
| 7.5 m   | 1068   | 1149    | 2415    | 2124   | 2322   | 4232    | 6136    | 639     | 134    |
| 0-2.5 m | 11.2   | 17.1    | 20.2    | 108    | 510    | 169     | 225     | 612     | 115    |

## Nitrate + Nitrite

|                 | May 9  | May 16  | May 25  | May 30 | June 6 | June 13 | June 21 | June 28 |        |
|-----------------|--------|---------|---------|--------|--------|---------|---------|---------|--------|
| Depth           |        |         |         |        |        |         |         |         |        |
| 0.0 m           | 5.6    | 6.4     | 1.3     | 1.6    | 3.8    | 9.7     | 4.4     | 6.8     |        |
| 1.0 m           | 4.4    | 14.4    | 0.0     | 1.6    | 3.1    | 10.1    | 6.5     | 5.7     |        |
| 2.0 m           | 9.7    | 17.7    | 0.0     | 0.0    | 3.8    | 10.3    | 10.3    | ---     |        |
| 4.0 m           | 40.0   | 16.0    | 0.0     | 0.0    | 4.8    | 10.7    | 15.9    | ---     |        |
| 6.0 m           | 52.5   | 8.8     | 0.4     | 0.0    | 4.4    | 13.0    | 17.9    | 14.4    |        |
| 7.5 m           | 47.2   | 15.8    | 0.0     | 0.0    | ---    | 14.3    | 12.3    | 9.2     |        |
| 0-2.5 m         | 12.0   | 12.9    | ---     | ---    | ---    | 10.4    | ---     | 8.1     |        |
|                 | July 5 | July 19 | July 25 | Aug 2  | Aug 8  | Aug 23  | Aug 28  | Sept 19 | Oct 17 |
| Depth<br>(ug/L) |        |         |         |        |        |         |         |         |        |
| 0.0 m           | 13.8   | 5.50    | 11.8    | 13.4   | 19.4   | 56.7    | 71.8    | 73.8    | 210    |
| 1.0 m           | 5.00   | 6.00    | 10.7    | 12.5   | 16.9   | 51.6    | 60.9    | 70.2    | 215    |
| 2.0 m           | 6.60   | 5.50    | 6.65    | 8.50   | 19.0   | 55.8    | 58.1    | 42.0    | 205    |
| 4.0 m           | 14.5   | 6.85    | 11.6    | 5.40   | 22.2   | 51.0    | 56.8    | 57.0    | 205    |
| 6.0 m           | 13.9   | 5.50    | 8.05    | 7.80   | 12.3   | 9.00    | 4.95    | 52.2    | 200    |
| 7.5 m           | 7.70   | 5.40    | 12.7    | 4.60   | 16.3   | 8.65    | 6.25    | 66.0    | 229    |
| 0-2.5 m         | ---    | 7.20    | 8.40    | ---    | 18.1   | 50.2    | 56.6    | 68.4    | 188    |

Table C-11. Sodium, Potassium, Calcium, and Magnesium (mg/L) in Halfmoon Lake, 1989

| Sodium    | May 9 | May 16 | May 25 | May 30 | June 6 | June 13 | June 21 | June 28 |
|-----------|-------|--------|--------|--------|--------|---------|---------|---------|
| Depth     |       |        |        |        |        |         |         |         |
| 0.0 m     | 16.6  | 20.1   | ---    | 21.9   | 20.4   | 20.8    | 20.3    | 21.4    |
| 1.0 m     | 16.5  | 20.1   | 18.9   | 21.2   | 20.3   | 20.6    | 20.4    | 21.4    |
| 2.0 m     | 16.4  | 20.1   | 18.4   | 21.1   | 20.4   | 20.5    | 20.5    | 21.4    |
| 4.0 m     | 16.4  | 20.0   | 17.9   | 22.1   | 20.5   | 20.3    | 20.5    | 21.3    |
| 6.0 m     | 15.8  | 20.1   | 17.5   | 21.9   | 20.1   | 20.4    | 19.8    | 21.4    |
| 7.5 m     | 15.9  | 20.1   | 17.3   | 21.8   | ---    | 20.3    | 20.3    | 21.5    |
| 0-2.5 m   | 15.7  | 20.2   | 17.1   | 22.0   | 20.3   | 20.4    | 20.3    | 21.4    |
| Potassium |       |        |        |        |        |         |         |         |
| Depth     |       |        |        |        |        |         |         |         |
| 0.0 m     | 14.1  | 14.0   | ---    | 12.3   | 14.5   | 14.5    | 13.7    | 14.4    |
| 1.0 m     | 14.2  | 14.2   | 13.6   | 12.3   | 14.5   | 14.5    | 13.7    | 14.4    |
| 2.0 m     | 14.2  | 14.1   | 13.5   | 11.9   | 14.6   | 14.5    | 13.8    | 14.5    |
| 4.0 m     | 14.2  | 14.1   | 13.7   | 11.6   | 14.7   | 14.5    | 13.9    | 14.3    |
| 6.0 m     | 14.2  | 14.1   | 13.4   | 11.4   | 14.7   | 14.4    | 13.8    | 14.5    |
| 7.5 m     | 14.4  | 14.2   | 13.3   | 11.2   | ---    | 14.7    | 14.1    | 14.7    |
| 0-2.5 m   | 14.4  | 14.2   | 13.3   | 10.9   | 14.5   | 14.6    | 13.9    | 14.3    |
| Calcium   |       |        |        |        |        |         |         |         |
| Depth     |       |        |        |        |        |         |         |         |
| 0.0 m     | 28.8  | 26.3   | ---    | 32.0   | 32.1   | 27.9    | 22.6    | 26.0    |
| 1.0 m     | 28.9  | 26.7   | 30.0   | 32.0   | 32.8   | 28.1    | 23.1    | 26.6    |
| 2.0 m     | 28.6  | 26.5   | 31.3   | 31.3   | 32.3   | 29.4    | 22.9    | 26.8    |
| 4.0 m     | 29.0  | 26.5   | 31.7   | 31.8   | 32.3   | 31.5    | 22.8    | 25.8    |
| 6.0 m     | 29.7  | 26.6   | 30.6   | 31.9   | 32.5   | 28.1    | 31.6    | 34.0    |
| 7.5 m     | 30.1  | 27.2   | 30.6   | 32.4   | ---    | 33.9    | 29.9    | 37.4    |
| 0-2.5 m   | 29.1  | 26.2   | 30.6   | 31.4   | 31.6   | 29.2    | 24.0    | 26.6    |
| Magnesium |       |        |        |        |        |         |         |         |
| Depth     |       |        |        |        |        |         |         |         |
| 0.0 m     | 14.5  | 11.5   | ---    | 13.4   | 10.4   | 12.8    | 10.1    | 11.3    |
| 1.0 m     | 13.7  | 11.3   | 11.3   | 13.4   | 9.68   | 11.2    | 9.08    | 10.4    |
| 2.0 m     | 14.1  | 12.2   | ---    | 13.1   | 9.78   | 11.2    | 10.1    | 11.2    |
| 4.0 m     | 14.8  | 12.8   | 11.4   | 13.3   | 9.64   | 11.9    | 9.72    | 10.3    |
| 6.0 m     | 15.4  | 10.9   | 11.4   | 13.5   | 10.4   | 11.6    | 10.3    | 10.2    |
| 7.5 m     | 12.3  | 10.9   | 10.9   | 13.1   | ---    | 10.8    | 9.14    | 12.3    |
| 0-2.5 m   | ---   | ---    | 11.8   | 13.0   | ---    | 11.9    | 10.3    | 10.5    |



Table C-11 (Cont'd)

|                  | July 5 | July 19 | July 25 | Aug 2 | Aug 8 | Aug 23 | Aug 28 | Sept 19 | Oct 17 | Oct 26 |
|------------------|--------|---------|---------|-------|-------|--------|--------|---------|--------|--------|
| <b>Sodium</b>    |        |         |         |       |       |        |        |         |        |        |
| Depth            |        |         |         |       |       |        |        |         |        |        |
| 0.0 m            | 21.9   | 21.1    | 20.9    | 21.2  | 22.0  | 21.5   | 21.6   | 22.7    | 23.7   | 21.0   |
| 1.0 m            | 21.7   | 20.9    | 21.1    | 20.4  | 22.3  | 21.5   | 21.5   | 22.6    | 24.0   | 21.0   |
| 2.0 m            | 22.0   | 20.9    | 20.8    | 20.7  | 22.2  | 21.6   | 21.7   | 22.6    | 24.0   | 20.8   |
| 4.0 m            | 22.7   | 21.2    | 19.3    | 21.1  | 22.2  | 21.4   | 21.6   | 22.9    | 24.2   | 20.8   |
| 6.0 m            | 23.3   | 20.9    | 20.5    | 21.0  | 22.4  | 21.4   | 21.5   | 22.9    | 24.4   | 20.7   |
| 7.5 m            | 21.5   | 20.7    | 21.0    | 20.9  | 22.5  | 21.4   | 21.1   | 22.9    | 24.5   | 20.7   |
| 0-2.5 m          | 21.3   | 18.4    | 20.5    | ---   | 22.2  | 21.5   | 21.6   | 22.9    | 24.7   | 20.9   |
| <b>Potassium</b> |        |         |         |       |       |        |        |         |        |        |
| Depth            |        |         |         |       |       |        |        |         |        |        |
| 0.0 m            | 14.5   | 14.3    | 14.3    | 13.7  | 14.7  | 14.7   | 14.7   | 13.6    | 14.4   | 14.9   |
| 1.0 m            | 14.4   | 14.2    | 14.4    | 13.6  | 14.7  | 14.8   | 14.6   | 13.6    | 14.4   | 14.9   |
| 2.0 m            | 14.5   | 14.3    | 14.3    | 13.8  | 14.8  | 14.9   | 14.9   | 13.4    | 14.4   | 14.9   |
| 4.0 m            | 14.5   | 14.7    | 12.4    | 14.0  | 15.0  | 14.8   | 14.8   | 13.6    | 14.4   | 14.8   |
| 6.0 m            | 14.7   | 14.3    | 14.2    | 14.3  | 15.2  | 15.2   | 14.9   | 13.3    | 14.4   | 14.8   |
| 7.5 m            | 14.8   | 14.6    | 14.9    | 14.3  | 15.5  | 15.2   | 15.3   | 13.6    | 14.4   | 14.8   |
| 0-2.5 m          | 14.5   | 12.5    | 13.9    | ---   | 14.8  | 14.6   | 14.7   | 13.5    | 14.4   | 15.0   |
| <b>Calcium</b>   |        |         |         |       |       |        |        |         |        |        |
| Depth            |        |         |         |       |       |        |        |         |        |        |
| 0.0 m            | 23.9   | 19.4    | 16.6    | 13.4  | 14.1  | 8.14   | 11.1   | 15.6    | 15.2   | 16.6   |
| 1.0 m            | 23.8   | 19.4    | 17.1    | 12.6  | 13.7  | 7.95   | 11.0   | 15.9    | 15.9   | 16.6   |
| 2.0 m            | 24.8   | 20.6    | 17.2    | 13.5  | 14.0  | 8.39   | 11.0   | 15.6    | 15.5   | 16.3   |
| 4.0 m            | 24.5   | 20.8    | 15.6    | 15.6  | 13.7  | 8.25   | 10.8   | 15.5    | 15.4   | 17.4   |
| 6.0 m            | 28.9   | 22.2    | 24.6    | 30.8  | 27.0  | 28.6   | 30.5   | 15.6    | 14.9   | 16.6   |
| 7.5 m            | 32.0   | 26.0    | 26.5    | 36.9  | 32.8  | 30.8   | 40.5   | 16.3    | 15.7   | 17.3   |
| 0-2.5 m          | ---    | ---     | ---     | ---   | 13.8  | 8.28   | 11.4   | 14.4    | 15.2   | 16.7   |
| <b>Magnesium</b> |        |         |         |       |       |        |        |         |        |        |
| Depth            |        |         |         |       |       |        |        |         |        |        |
| 0.0 m            | 13.5   | 12.4    | 12.0    | 13.2  | 13.3  | 10.4   | 10.4   | 9.00    | 12.0   | 12.4   |
| 1.0 m            | 12.0   | 11.9    | 12.4    | 11.7  | 12.4  | 9.82   | 10.5   | 9.67    | 12.3   | 12.5   |
| 2.0 m            | 13.2   | 12.9    | 12.2    | 12.2  | 13.1  | 9.78   | 10.3   | 8.91    | 12.7   | 12.4   |
| 4.0 m            | 12.8   | 13.6    | 9.85    | 11.9  | 12.9  | 9.71   | 10.3   | 10.1    | 12.6   | 12.3   |
| 6.0 m            | 13.1   | 12.4    | 12.1    | 12.9  | 13.9  | 13.2   | 13.5   | 9.23    | 12.1   | 12.0   |
| 7.5 m            | 13.9   | 13.0    | 14.0    | 13.4  | 14.7  | 12.5   | 14.6   | 8.84    | 12.7   | 12.7   |
| 0-2.5 m          | ---    | ---     | 12.0    | ---   | 12.9  | 9.61   | 10.1   | 8.42    | 12.4   | 12.3   |

Table C-12. Phytoplankton species composition in Halfmoon Lake. Biomass estimates (blue-green  $\mu\text{m}/\text{ml}$ ; all others cells/ $\text{ml}$ ).

[illegible]

Table C-13. Sediment core (mg/g) and Porewater analyses

## Core 4; July 13, 1988

| Depth(cm) | % WATER | Mn    | TP   | Cu    | Fe   | Ca   | Mg   | Na    | K    | Ca:TP |
|-----------|---------|-------|------|-------|------|------|------|-------|------|-------|
| 0-1       | 87.8    | 0.818 | 2.06 | 0.038 | 19.9 | 39.6 | 4.23 | 0.434 | 2.41 | 19.2  |
| 1-2       | 91.9    | 0.608 | 1.24 | 0.038 | 19.1 | 38.9 | 4.53 | 0.283 | 2.24 | 31.4  |
| 2-3       | 90.7    | 0.577 | 1.44 | 0.040 | 19.2 | 25.3 | 4.23 | 0.370 | 2.44 | 17.6  |
| 3-4       | 90.0    | 0.646 | 1.65 | 0.043 | 18.9 | 49.7 | 4.34 | 0.270 | 2.30 | 30.1  |
| 4-5       | 89.4    | 0.535 | 1.49 | 0.047 | 18.8 | 47.1 | 4.40 | 0.301 | 2.40 | 31.6  |
| 5-6       | 89.4    | 0.627 | 1.49 | 0.053 | 21.2 | 38.7 | 4.47 | 0.302 | 2.53 | 25.9  |
| 6-7       | 89.0    | 0.657 | 1.46 | 0.062 | 19.8 | 23.3 | 4.36 | 0.286 | 2.59 | 16.0  |
| 7-8       | 88.6    | 0.750 | 1.58 | 0.070 | 21.1 | 18.0 | 4.55 | 0.237 | 2.75 | 11.4  |
| 8-9       | 88.8    | 0.621 | 1.42 | 0.076 | 20.3 | 20.1 | 4.44 | 0.254 | 2.49 | 14.2  |
| 9-10      | 88.8    | 0.570 | 1.42 | 0.109 | 19.7 | 19.4 | 4.36 | 0.233 | 2.28 | 13.7  |
| 10-12     | 88.6    | 0.544 | 1.33 | 0.034 | 18.4 | 12.7 | 4.05 | 0.248 | 2.11 | 9.5   |
| 12-13     | 88.5    | 0.530 | 1.30 | 0.034 | 17.9 | 13.4 | 3.91 | 0.208 | 2.08 | 10.3  |

## Core N1; September 19, 1989

| Depth(cm) | % WATER | Mn    | TP   | Cu    | Fe   | Ca   | Mg   | Na    | K    | Ca:TP |
|-----------|---------|-------|------|-------|------|------|------|-------|------|-------|
| 0-1       | 94.0    | 0.303 | 1.44 | 0.031 | 12.3 | 73.5 | 4.62 | 0.587 | 2.27 | 51.0  |
| 1-2       | 92.9    | 0.348 | 1.67 | 0.035 | 14.4 | 47.0 | 4.58 | 0.451 | 2.40 | 28.1  |
| 2-3       | 91.7    | 0.304 | 1.49 | 0.045 | 15.1 | 41.1 | 4.90 | 0.444 | 2.46 | 27.6  |
| 3-4       | 91.0    | 0.359 | 1.48 | 0.052 | 18.8 | 28.5 | 6.93 | 0.415 | 2.91 | 19.3  |
| 4-5       | 90.3    | 0.339 | 1.45 | 0.056 | 18.1 | 24.3 | 5.44 | 0.390 | 2.67 | 16.8  |
| 5-6       | 90.2    | 0.327 | 1.44 | 0.069 | 18.8 | 18.0 | 5.80 | 0.408 | 2.75 | 12.5  |
| 6-7       | 90.2    | 0.308 | 1.41 | 0.076 | 19.4 | 13.6 | 5.82 | 0.382 | 2.88 | 9.6   |
| 7-8       | 90.7    | 0.325 | 1.39 | 0.078 | 17.9 | 13.8 | 5.71 | 0.382 | 2.75 | 9.9   |
| 8-9       | 90.3    | 0.357 | 1.34 | 0.075 | 20.2 | 17.3 | 6.12 | 0.424 | 2.62 | 12.9  |
| 9-10      | 90.1    | 0.336 | 1.33 | 0.066 | 20.4 | 13.9 | 6.05 | 0.410 | 2.52 | 10.5  |
| 10-11     | 89.9    | 0.332 | 1.35 | 0.053 | 18.8 | 11.7 | 6.10 | 0.386 | 2.44 | 8.7   |
| 11-12     | 89.8    | 0.341 | 1.43 | 0.043 | 20.1 | 10.7 | 6.04 | 0.411 | 2.49 | 7.5   |
| 12-13     | 90.1    | 0.354 | 1.41 | 0.031 | 20.5 | 11.2 | 5.48 | 0.401 | 2.47 | 7.9   |
| 13-14     | 90.2    | 0.347 | 1.40 | 0.027 | 20.9 | 11.1 | 5.39 | 0.403 | 2.37 | 7.9   |
| 14-15     | 89.1    | 0.357 | 1.48 | 0.025 | 22.4 | 10.9 | 5.57 | 0.410 | 2.43 | 7.4   |
| 24-25     | 89.1    | 0.335 | 1.57 | 0.021 | 21.2 | 6.8  | 4.28 | 0.420 | 2.15 | 4.3   |

## Porewater Chemistry mean values +/- S.E.

| Depth in<br>Sediment (cm) | SRP<br>(ug/L) | DO<br>(mg/L) | Iron<br>(mg/L) |
|---------------------------|---------------|--------------|----------------|
| superstitial              | 11.5+/-3      | 5.7+/-0.6    | 0.72           |
| 0-5                       | 86.4+/-7      | 1.6+/-0.05   | 2.39           |
| 5-10                      | 82.9+/-8      | 1.3+/-0.2    | 1.47           |
| 10-15                     | 78.3+/-4      | ---          | 1.74           |
| 15-20                     | 75.8+/-1      | ---          | 2.19           |

Table C-14. Temperature (C), DO (mg/L), TP (ug/L), TDP (ug/L), and Chla (ug/L) in Halfmoon Lake; winter 1989-90.

|                    | 27 Nov | 7 Dec | 28 Dec | 11 Jan | 25 Jan | 8 Feb | 21 Feb   | 5 March | 19 March | 3 April |
|--------------------|--------|-------|--------|--------|--------|-------|----------|---------|----------|---------|
| Ice Thickness (cm) | 15.0   | 22.0  | 25.0   | 34.5   | 42.5   | 55.0  | 58.0     | 68.5    | 65.0     | 53.5    |
| Snow (cm)          | 3.5    | 3.5   | 0.0    | 0 to 5 | 0 to 2 | 3.0   | 10 to 15 | 1.0     | 1.0      | 0.0     |
| Temp. (C)          |        |       |        |        |        |       |          |         |          |         |
| 0 m                | 1.9    | 0.7   | 0.8    | 0.4    | 0.2    | 1.0   | 0.3      | 0.5     | 0.4      | 1.4     |
| 1 m                | 3.3    | 2.9   | 2.8    | 2.3    | 2.5    | 1.9   | 1.5      | 0.9     | 1.5      | 4.6     |
| 2 m                | 3.4    | 3.1   | 3.3    | 3.4    | 3.1    | 2.8   | 3.1      | 3.4     | 3.4      | 4.4     |
| 3 m                | 3.5    | 3.2   | 3.5    | 3.5    | 3.2    | 3.0   | 3.3      | 3.5     | 3.6      | 4.0     |
| 4 m                | 3.6    | 3.3   | 3.6    | 3.7    | 3.7    | 3.3   | 3.4      | 3.6     | 3.7      | 4.0     |
| 5 m                | 3.7    | 3.5   | 3.8    | 3.9    | 4.0    | 3.6   | 3.8      | 3.8     | 3.8      | 4.0     |
| 6 m                | 3.9    | 3.7   | 4.0    | 4.1    | 4.0    | 3.8   | 4.1      | 4.2     | 4.0      | 4.0     |
| 7 m                | 4.2    | 4.0   | 4.3    | 4.4    | 3.9    | 4.0   | 4.4      | 4.6     | 4.2      | 4.2     |
| 8 m                | 4.8    | 4.5   | 4.9    | 4.8    | 4.4    | 4.9   | 5.2      | 5.1     | 5.0      | 4.7     |
| D.O. (mg/L)        |        |       |        |        |        |       |          |         |          |         |
| 1 m                | 11.4   | 10.7  | 9.25   | 8.28   | 7.22   | 5.96  | 4.51     | 4.83    | 10.9     | 16.1    |
| 2 m                | 11.3   | 10.6  | 9.08   | 7.79   | 6.95   | 5.83  | 3.44     | 3.35    | 4.53     | 16.0    |
| 3 m                | 11.2   | 10.4  | 9.06   | 7.50   | 6.84   | 5.55  | 3.35     | 2.69    | 2.41     | 14.0    |
| 4 m                | 11.0   | 9.42  | 8.90   | 7.32   | 6.34   | 4.59  | 3.16     | 2.39    | 0.97     | 5.35    |
| 5 m                | 10.6   | 9.04  | 6.00   | 5.52   | 6.18   | 4.27  | 2.61     | 1.20    | 0.99     | 3.98    |
| 6 m                | 9.54   | 8.65  | 1.31   | 4.86   | 3.95   | 4.24  | 2.43     | 1.02    | 0.63     | 2.46    |
| 7 m                | 5.60   | 4.30  | 1.82   | 1.65   | 2.35   | 2.16  | 1.95     | 0.59    | 0.40     | 0.68    |
| 8 m                | 2.10   | 1.36  | 0.73   | 0.42   | 0.26   | 1.30  | 0.42     | 0.38    | 0.00     | 0.57    |
| TP (ug/L)          |        |       |        |        |        |       |          |         |          |         |
| 1 m                | 53.3   | 48.4  | 50.0   | 50.5   | 58.4   | 60.3  | 73.5     | 57.7    | 73.8     | 50.4    |
| 2 m                | 52.6   | 52.0  | 49.8   | 47.3   | 52.8   | 57.3  | 60.8     | 59.9    | 63.4     | 59.6    |
| 4 m                | 50.4   | 48.5  | 49.2   | 48.3   | 53.2   | 57.3  | 59.7     | 60.1    | 55.4     | 77.9    |
| 6 m                | 50.2   | 49.2  | 84.7   | 64.3   | 67.6   | 63.1  | 84.8     | 93.9    | 75.6     | 90.9    |
| 8 m                | 128    | 113   | 224    | 206    | 115    | 206   | 284      | 189     | 280      | 142     |
| TDP (ug/L)         |        |       |        |        |        |       |          |         |          |         |
| 1 m                | 29.3   | 30.5  | 35.5   | 30.7   | 34.5   | 37.7  | 43.0     | 34.3    | 31.0     | 19.6    |
| 2 m                | 29.3   | 33.8  | 34.9   | 31.3   | 32.6   | 39.6  | 41.3     | 40.0    | 35.4     | 21.0    |
| 4 m                | 28.7   | 33.5  | 34.8   | 33.2   | 34.5   | 41.2  | 43.5     | 41.2    | 49.2     | 24.1    |
| 6 m                | 28.7   | 33.5  | 58.1   | 48.5   | 46.7   | 45.0  | 64.1     | 71.7    | 57.6     | 44.0    |
| 8 m                | 46.1   | 61.7  | 132    | 133    | 78.5   | 163   | 178      | 162     | 229      | 107     |
| Chla (ug/L)        | 4.51   | 2.51  | 1.19   | 1.85   | 10.2   | 5.33  | 5.29     | 3.48    | 36.7     |         |



Table C-15. pH, Alkalinity, Nitrite + Nitrate, and Ammonium in Halfmoon Lake; Winter 1989-90.

|   | 27 Nov | 7 Dec | 28 Dec | 11 Jan | 25 Jan | 8 Feb | 21 Feb | 5 March | 19 March | 3 April |
|---|--------|-------|--------|--------|--------|-------|--------|---------|----------|---------|
| pH  |        |       |        |        |        |       |        |         |          |         |
| 1 m   | 7.72   | 8.86  | 8.82   | 8.61   | 8.67   | 8.37  | ---    | 8.23    | 8.49     | 8.94    |
| 2 m   | 8.70   | 8.60  | 8.78   | 8.58   | 8.67   | 8.43  | ---    | 8.23    | 8.34     | 8.90    |
| 4 m   | 8.82   | 8.57  | 8.78   | 8.55   | 8.60   | 8.42  | ---    | 8.25    | 8.16     | 8.25    |
| 6 m   | 8.42   | 8.65  | 8.18   | 8.27   | 8.48   | 8.35  | ---    | 8.25    | 8.16     | 8.25    |
| 8 m   | 7.95   | 8.02  | 7.94   | 7.90   | 8.19   | 8.05  | ---    | 8.09    | 8.03     | 8.26    |
| Tot. Alkalinity<br>(mg/L as CaCO <sub>3</sub> ) |        |       |        |        |        |       |        |         |          |         |
| 1 m   | 128    | 143   | 136    | 148    | 152    | 146   | ---    | 147     | 145      | 126     |
| 2 m   | 129    | 134   | 136    | 146    | 146    | 144   | ---    | 149     | 143      | 141     |
| 4 m   | 138    | 136   | 136    | 140    | 144    | 146   | ---    | 149     | 145      | 143     |
| 6 m   | 136    | 138   | 142    | 138    | 146    | 145   | ---    | 151     | 149      | 147     |
| 8 m   | 144    | 147   | 160    | 157    | 159    | 161   | ---    | 160     | 167      | 157     |
| Carbonate (mg/L)                                |        |       |        |        |        |       |        |         |          |         |
| 1 m   | 7.31   | 7.79  | 6.59   | 8.99   | 6.12   | 0.48  | ---    | 0.00    | 3.36     | 9.83    |
| 2 m   | 7.07   | 3.60  | 4.92   | 5.88   | 6.59   | 1.56  | ---    | 0.00    | 0.00     | 9.59    |
| 4 m   | 7.31   | 5.16  | 5.60   | 3.12   | 3.36   | 1.68  | ---    | 0.00    | 0.00     | 0.00    |
| 6 m   | 2.76   | 8.27  | 0.00   | 0.00   | 2.16   | 0.24  | ---    | 0.00    | 0.00     | 0.00    |
| 8 m   | 0.00   | 0.00  | 0.00   | 0.00   | 0.00   | 0.00  | ---    | 0.00    | 0.00     | 0.00    |
| Bicarbonate (mg/L)                              |        |       |        |        |        |       |        |         |          |         |
| 1 m   | 149    | 159   | 152    | 162    | 172    | 177   | ---    | 179     | 170      | 134     |
| 2 m   | 150    | 157   | 155    | 166    | 164    | 173   | ---    | 182     | 174      | 152     |
| 4 m   | 154    | 155   | 154    | 164    | 168    | 174   | ---    | 181     | 177      | 174     |
| 6 m   | 160    | 151   | 173    | 168    | 173    | 176   | ---    | 184     | 182      | 179     |
| 8 m   | 176    | 179   | 195    | 192    | 194    | 197   | ---    | 195     | 208      | 192     |
| NO <sub>2</sub> + NO <sub>3</sub> (ug/L)        |        |       |        |        |        |       |        |         |          |         |
| 1 m   | 216    | ---   | ---    | 169    | 298    | 353   | 502    | 571     | 330      | 685     |
| 2 m   | 208    | ---   | ---    | 179    | 296    | 349   | 480    | 590     | 522      | 118     |
| 4 m   | 211    | ---   | ---    | 179    | 264    | 355   | 503    | 620     | 484      | 215     |
| 6 m   | 215    | ---   | ---    | 273    | 220    | 329   | 333    | 395     | 433      | 91.2    |
| 8 m   | 138    | ---   | ---    | 33.3   | 70.4   | 72.4  | 138    | 68.4    | 33.4     | 29.9    |
| NH <sub>4</sub> <sup>+</sup>                    |        |       |        |        |        |       |        |         |          |         |
| 1 m   | 178    | ---   | ---    | 172    | 128    | 136   | 42.8   | 4.58    | 7.39     | 19.1    |
| 2 m   | 178    | ---   | ---    | 149    | 146    | 133   | 45.0   | 4.21    | 11.4     | 14.9    |
| 4 m   | 178    | ---   | ---    | 139    | 161    | 152   | 52.4   | 9.19    | 130      | 93.6    |
| 6 m   | 185    | ---   | ---    | 174    | 297    | 190   | 384    | 373     | 203      | 344     |
| 8 m   | 765    | ---   | ---    | 1257   | 631    | 882   | 1620   | 1142    | 1837     | 1068    |

Table C-16. Sodium, Potassium, Calcium, and Magnesium (mg/L) in Halfmoon Lake; Winter 1989-90

| Sodium    | 27 Nov | 7 Dec | 28 Dec | 11 Jan | 25 Jan | 8 Feb | 21 Feb | 5 March | 19 March | 3 April |
|-----------|--------|-------|--------|--------|--------|-------|--------|---------|----------|---------|
| Depth     |        |       |        |        |        |       |        |         |          |         |
| 1 m       | 21.7   | 21.9  | 21.7   | 22.7   | 22.7   | 23.0  | 23.5   | 23.3    | 24.6     | 20.5    |
| 2 m       | 21.7   | 21.6  | 22.1   | 22.4   | 22.5   | 22.3  | 22.9   | 23.0    | 24.1     | 22.7    |
| 4 m       | 21.5   | 21.3  | 22.1   | 22.4   | 22.9   | 21.7  | 23.0   | 22.9    | 23.7     | 23.2    |
| 6 m       | 21.6   | 21.5  | 21.9   | 22.4   | 22.8   | 21.7  | 22.6   | 22.8    | 23.8     | 23.3    |
| 8 m       | 21.7   | 22.0  | 22.3   | 23.2   | 24.7   | 21.9  | 22.4   | 22.4    | 24.7     | 24.7    |
| Potassium |        |       |        |        |        |       |        |         |          |         |
| Depth     |        |       |        |        |        |       |        |         |          |         |
| 1 m       | 14.7   | 14.6  | 14.4   | 14.7   | 14.9   | 15.0  | 15.3   | 15.1    | 16.5     | 14.0    |
| 2 m       | 14.7   | 14.5  | 14.7   | 14.5   | 14.7   | 15.0  | 15.0   | 14.8    | 16.1     | 15.5    |
| 4 m       | 14.5   | 14.3  | 14.8   | 14.7   | 14.8   | 14.8  | 15.0   | 14.7    | 15.9     | 15.7    |
| 6 m       | 14.5   | 14.4  | 14.6   | 14.3   | 14.6   | 14.7  | 14.7   | 14.6    | 16.0     | 15.8    |
| 8 m       | 14.5   | 14.5  | 14.90  | 14.9   | 14.8   | 14.8  | 14.5   | 14.4    | 16.2     | 16.8    |
| Calcium   |        |       |        |        |        |       |        |         |          |         |
| Depth     |        |       |        |        |        |       |        |         |          |         |
| 1 m       | 18.0   | 17.6  | 17.0   | 19.4   | 20.3   | 20.6  | 24.0   | 23.6    | 22.3     | 20.0    |
| 2 m       | 17.1   | 18.1  | 17.7   | 18.8   | 20.0   | 23.8  | 24.0   | 23.6    | 22.3     | 22.1    |
| 4 m       | 18.8   | 17.7  | 18.2   | 20.4   | 20.0   | 20.5  | 23.7   | 23.2    | 23.1     | 22.7    |
| 6 m       | 19.0   | 18.9  | 18.7   | 19.0   | 20.4   | 20.7  | 24.9   | 23.2    | 24.5     | 23.5    |
| 8 m       | 20.9   | 21.2  | 22.9   | 24.5   | 23.8   | 23.9  | 28.5   | 27.0    | 29.6     | 26.5    |
| Magnesium |        |       |        |        |        |       |        |         |          |         |
| Depth     |        |       |        |        |        |       |        |         |          |         |
| 1 m       | 12.1   | 11.6  | 11.7   | 12.5   | 12.8   | 12.1  | 13.8   | 13.6    | 14.1     | 12.2    |
| 2 m       | 12.3   | 11.8  | 11.9   | 12.2   | 13.2   | 12.8  | 13.5   | 13.4    | 14.0     | 13.6    |
| 4 m       | 12.0   | 11.6  | 12.3   | 13.6   | 13.3   | 12.4  | 13.4   | 13.5    | 14.0     | 13.8    |
| 6 m       | 11.5   | 11.6  | 11.5   | 12.3   | 13.7   | 12.3  | 13.3   | 13.4    | 14.1     | 13.8    |
| 8 m       | 12.2   | 12.0  | 12.6   | 13.0   | 14.3   | 12.6  | 13.4   | 13.4    | 14.8     | 14.5    |







N.L.C. - B.N.C.



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